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MINUTES

OF THE ~~EIGHTH~~

EXPLOSIVES SAFETY SEMINAR

ON

HIGH-ENERGY PROPELLANTS

GEO. C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

9-11 August 1966

Sponsor

ARMED SERVICES EXPLOSIVES SAFETY BOARD
Washington, D. C. 20315

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NOV 3 1966

Host

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PREFACE

This is a record of the proceedings of the Eighth Annual Explosives Safety Seminar on High Energy Propellants held at the G. C. Marshall Space Flight Center, Huntsville, Alabama, 9, 10, and 11 August 1966.

The Armed Services Explosives Safety Board (ASESB) sponsors the annual Seminar as a means of providing an exchange of current information on explosives safety between those segments of Government and industry concerned with high energy propellants. Selected papers are presented by the participants during the course of the Seminar, and a free discussion of the subject matter is encouraged.

The material contained herein represents reports and opinions of the participants, and is a product of the individual or organization which he represents. The ASESB does not vouch for the accuracy of the facts presented, and does not necessarily endorse the opinions expressed.

Rapid and widespread exchange of information concerning explosives incidents and accidents is a vital component of a cooperative effort on the part of Government and industry to develop effective means of prevention in their safety programs. Questions and comments concerning the material herein should be directed to the individual speakers or their organization.

The Armed Services Explosives Safety Board, Nassif Building, Washington, D. C., 20315, should be advised of errors or other corrections that may be required in the text.

Appreciation is expressed to all participants for their interest, and their active role in promoting the cause of explosives safety within the Department of Defense and in the industries represented at the Seminar.

R. E. Johnson
R. E. JOHNSON
Captain, USN
Chairman, ASESB
19 September 1966

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Minutes of the

Eighth Annual

EXPLOSIVES SAFETY SEMINAR ON HIGH ENERGY PROPELLANTS

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CAPT. RICHARD E. JOHNSON, USN
CHAIRMAN
ARMED SERVICES EXPLOSIVES SAFETY BOARD

It is a pleasure and a reward for the work that we do to arrange this meeting to see you people here and to know the difficulties that many of you have experienced in arriving. This Eighth Annual Seminar is hosted by the National Aeronautics and Space Administration and specifically by the Marshall Space Flight Center. There is no specific person I can single out for our deep thanks because everyone's cooperation and the way they've done things is so highly professional. It is a vivid example of why the Space Administration is having such successes in all their work. We are fortunate and honored this morning to have the Director of the Marshall Space Flight Center, Dr. Wernher von Braun with us. He will say a word to you at this time. Dr. von Braun.

DR. WERNHER VON BRAUN, DIRECTOR
MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

Capt. Johnson, Members of the Board, and delegates from the Services, NASA, and industry.

It is a pleasure to welcome you to the Marshall Space Flight Center for your Eighth Annual Seminar. We are delighted to be your host for this important meeting.

We hope that your trip to Huntsville was made without too many travel delays or inconveniences, as a result of the airlines strike. While you are here, I'm sure "Buster" Roberts, our safety expert, is doing everything possible to make your stay enjoyable. And if you should get stranded here, "Buster" might even lend you $100, as one of the airlines offered to do for its travelers stranded in Europe because of the strike.

NASA, of course, shares with the Armed Services a deep interest in safety in the use of high energy propellants, liquids as well as solids, and we have found these meetings with you very beneficial in the past. In fact, NASA owes a tremendous debt of gratitude to the Armed Services for countless contributions to its space efforts. The early achievements of our young agency were based almost entirely upon the tremendous capabilities of the Armed Services. The Army provided the Redstone launch vehicle for the nation's first satellite. The Air Force provided the Atlas and Titan II, the launch vehicles for the Mercury and Gemini shots. And the Navy has recovered our astronauts from the ocean and brought them safely home.

We rely heavily upon the knowledge and experience of the members of the Armed Services in many other ways. Here at the Marshall Center, for instance, we have on our staff 30 members of the Armed Forces who are still on active duty. Air Force Brigadier General Edmund O'Connor heads our Industrial Operations, which is responsible for spending more than 90 per cent of our dollars.

Our deep interest in safety in the handling and storage of propellants can be illustrated by one example. Our Apollo/Saturn V launch vehicle and spacecraft will use a total of 91 liquid and solid propellant motors for the manned lunar landing mission. These motors receive a great deal of ground testing and consume huge quantities of propellants before they are flight rated. The fact that this ground testing is conducted with the highest degree of safety reflects the dedication and concern of this Board.

I shudder to think of the risks we accepted matter-of-factly during our earliest rocket experiments. Art Rudolph, our Saturn V program office manager, has been guilty of throwing a lighted match in the nozzle of a small engine when the igniter failed. And we have climbed all over a pressurized V-2.

There is too much at stake today to take such unnecessary risks. The lives of our people are all-important. And a great deal of money has been invested in the items being tested, and the test facilities where the propellants are handled.

I must confess, somewhat ruefully, that we have found a way of blowing up rocket stages even without propellants. We simply overpressurize them. Our Mississippi Test Facility is just getting back into operation after an S-II stage erupted in the stand during a pressurization test. No one was seriously injured, but the stage was destroyed, and the stand suffered extensive damages. We also overpressurized an S-IV stage, and it blew up. But this time we did it deliberately, and the test stand wasn't damaged. We waited until we got the stage in orbit, and had concluded several experiments in venting the liquid hydrogen aboard.

All upper stages of the Saturns use the powerful liquid hydrogen and liquid oxygen propellant combination. We took a big gamble several years ago in selecting liquid hydrogen for the Saturns. No liquid hydrogen engine had yet been flown. Cautious people remembered the Von Hindenburg dirigible, and the tragic explosion of its gaseous hydrogen fuel. Hydrogen had been called a "devil gas," and some people said it would never be tamed.

But we needed this high energy fuel, which provides 40 per cent more thrust per pound of propellant flow per second than the kerosene used in the first stages of the Saturns. At 423 degrees below zero, liquid hydrogen is one of the coldest things in existence. And the liquid oxygen is a fairly cold 293 degrees below zero. While they explode when mixed, they burn beautifully when brought together under proper controls, developing temperatures of 5,500 degrees fahrenheit. You know the story. Liquid hydrogen has been tamed.

We expected numerous hazards and difficulties in handling hydrogen, and we respected them. We still do.

Some of the major space goals of the decade depend for success on the complete mastery of liquid hydrogen technology. We shall continue to treat this volatile fuel with the utmost respect.

We are deeply grateful to this Board for its role in the success of our program thus far, and urge you to continue your good work, and to continue the exchange of information in seminars such as this one.

Don't forget, the success of a mission to Mars will depend on the use of liquid hydrogen in nuclear powered rockets and will involve problems such as the safe transfer of liquid hydrogen in earth orbit, and its storage for months in the hard vacuum of space.

Thank you.

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Bruce M. Docherty
Assistant General Counsel, Department of the Army

Each year the Armed Services Explosives Safety Board has asked the General Counsel of the Army to make an attorney available for attendance at its Explosives Safety Seminar on High Energy Propellants. Those who have attended prior Seminars are probably aware of the reasons for attendance of counsel. I will restate those reasons briefly.

It has long been recognized that information and advice obtained through activities such as this Seminar are beneficial to the operations of the Government. Consistent with that recognition certain standards have been prescribed by Presidential Executive Order to insure that committees and similar groups sponsored by the Government for the purpose of obtaining such information or advice shall function at all times in consonance with the antitrust and conflict of interest laws.

This Seminar is being conducted in accordance with the standards applicable to this type of meeting. It is felt, however, that since any such meeting as this is subject to the provisions of the antitrust laws, a Government attorney should be present as an added protection to the Government and to all participants.

I am not here to present the full and free exchange of information. That would defeat the purpose of the Seminar. The primary reason for my presence is to guard against the inadvertent consideration of any subject which might bring the Seminar within some aspect of the antitrust laws. This is not likely in view of the excellent manner in which these Seminars are always conducted.

The agenda has been prepared with a view to permitting free discussion of the topics to be considered. I will be present throughout all the sessions. If at any time I think we are getting into an area which might raise antitrust implications, I will call this to the Chairman's attention so that any such discussion may be avoided.

I will also be available during and outside meetings for the consideration of antitrust, conflict of interest or other legal problems which may arise. I should add that I have always greatly enjoyed these Seminars and that I am very happy to be back again today.

NASA/USAF LIQUID PROPELLANT HAZARD PROGRAM (PYRO)

by

John W. Marshall
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

and

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ABSTRACT

The Liquid Propellant Blast Hazards Program which is being conducted by the AFRPL at Edwards AFB, California, is a jointly funded NASA/USAF effort. Its purpose is to develop a reliable philosophy for predicting the credible damage potential which may be experienced from an accidental explosion of liquid propellants during launch operations of military missiles or space vehicles.

Three propellant combinations are being investigated: N_2O_4/ 50% UDMH - 50% N_2H_4, LO_2/RP-1 and LO_2/LH_2. The effects of propellant mass, length-to-diameter ratio, failure mode, and ignition delay time are some of the variables being considered in this program. The mass effects will be determined using 200, 1000, and 25000 lb total propellant weight test articles.

Measurements of peak overpressure, positive-phase impulse, stagnation pressure, heat flux, fireball profile, and fireball temperature will be made for each of the tests.

It is hoped that a correlation between the various parameters and explosive yield will be obtained so that methods can be developed for predicting the credible damage potential of liquid propellant explosions.

This paper presents a brief description of the overall program and summarizes some of the results to date.

Section 1

INTRODUCTION

The NASA/USAF Liquid Propellant Blast Hazards Program, known as Project PYRO, is being conducted by the Air Force Rocket Propulsion Laboratory (AFRPL) for the NASA Marshall Space Flight Center, Huntsville, Alabama. The program was initiated in August 1963 and is expected to be completed by July 1967. The NASA Program Director is Mr. W. A. Riehl and the AFRPL Program Manager is Mr. J. W. Marshall. URS Corporation, with Mr. A. B. Willoughby as principal investigator, is providing experiment design, data reduction, data analysis and reporting, design and construction of test articles, and consulting services under contract to the AFRPL. This program is being funded by the NASA Marshall Space Flight Center, the NASA Kennedy Space Center, the Air Force Eastern Test Range, and the AEC/Sandia Laboratory, Albuquerque, New Mexico. Total funding is approximately 3.4 million dollars.

The purpose of this program is to develop a reliable philosophy for predicting the credible damage potential which may be experienced from an accidental explosion of liquid propellants during launch or test operations of military missiles or space vehicles. Such information is required for the siting of static and launch facilities, for vehicle and payload design, for launch operations, etc. The propellant combinations of N_2O_4/50% UDMH - 50% N_2H_4, LO_2/RP-1 and LO_2/LH_2 are being investigated in the current program. Size effects will be determined by testing articles of 200, 1000, and 25000 lb total propellant weight. No specific missile configurations are being simulated so that data accumulated will be suitable for application to any missile system using these propellant combinations. A total of approximately 225 tests is planned.

The overall design of the experimental program is described in Section 2 of this paper. Included are descriptions of the basic testing conditions and the parameter variation for each condition. Emphasis is given to the cryogenic portion of the program. The instrumentation system used in the test program for documenting the blast and thermal environments of the propellant explosion is described in Section 3 and typical results obtained from the test program are given in Sections 4 and 5. Section 4 covers the controlled failure test of a full-scale Saturn S-IV and Section 5, the high-velocity impact test series. A brief description of the types of tests currently in progress is given in Section 6. For more detailed discussion of the

information covered in Sections 2, 3, and 5, refer to AFRPL TR-65-144, (Ref 1).

Section 2

DESIGN OF EXPERIMENTAL PROGRAM

The information available at the time the basic test design philosophy was being established indicated that the cryogenic propellants tend to have explosive characteristics which are significantly different from hypergolic propellants. For cryogenic propellants, scaled model tests had indicated that significant explosive yields are possible for a large variety of missile and failure conditions (Refs. 2 - 7). Thus, it was clear that for these cryogenic propellants a comprehensive testing program would be necessary to evaluate the effect of the various important parameters of the process. However, for hypergolic propellants the test results suggested that it is virtually impossible to obtain significant explosive yields under normal mixing conditions (Refs. 8 - 10). If this were true, then it would not be necessary to cover as large a range of test conditions as with cryogenic propellants. Accordingly, it was decided that initially the hypergolic propellant combination would be considered separately from the cryogenic combinations and that the early testing of it would be concentrated on certain limiting conditions which tend to maximize the explosive effects. The results of these tests would indicate whether or not further testing of the hypergolic propellant combination would be necessary and, if so, what conditions should be covered.

The desirable philosophy to use for the cryogenic test program was more difficult to find because of the large number of potentially important variables and the desire to make the results as general as possible, i.e., applicable to any tankage configuration, failure mode, and ignition source configuration. Five basic variables of the initial configuration are considered of prime concern with regard to the ultimate explosive yield: the propellant type, the tank configuration, the failure mode, the launch pad geometry, and the ignition-source configuration. The basic problem in Project PYRO is thus to determine the relation between these basic variables and the explosive effects. This is illustrated in Figure 1.

It should be noted that Project PYRO is basically limited to the region of Figure 1 enclosed by the dashed lines, i.e., the end point of this study is the prediction of explosive effects as a

function of the time of ignition. Although some information will no doubt be obtained regarding credible ignition times, a specific study leading to methods for predicting these times is beyond the scope of the current program.

In formulating the general approach to be used in Project PYRO, it was recognized that the basic variables, except for the time of ignition, were not quantitative parameters, and thus it would not be desirable to go directly from them to the explosive effects as indicated in Figure 1.

A more suitable set of test parameters was developed by recognizing that these basic variables controlled the space - time history of the propellants, i.e., how the propellants flow or spill out of their tanks and come into contact with each other, and that the space - time history, in turn, controlled the mixing process and, thus, the explosive effects. Accordingly, the basic variables were replaced by a set of initial parameters which determine the space - time history of the propellants.

Figure 2 shows the three basic boundary conditions selected for study. The specific initial-condition parameters vary to some extent with each boundary condition but typically include those necessary to describe the spatial and velocity distribution of the propellants at the moment of their initial contact.

It was also recognized at the inception of the PYRO Program that it would be necessary to conduct the great majority of the explosive testing of propellant spillages in model scales because the cost of a statistically adequate number of full-scale tests would be prohibitive, and thus it would be necessary to develop scaling relations to apply the model-scale test results to full-scale situations.

Although several different scales of testing were included in the main PYRO test program, it was believed that the large number of test conditions of interest combined with the high costs of large-scale tests make their use undesirable as the basic source of information for development of scaling relations. Rather they should be used primarily to verify postulated scaling relations, and the basic scaling relations should be developed from a combination of theoretical analyses and special experimental studies.

The Basic PYRO test approach, involving model-scale tests and the space - time history generalization, is illustrated in Figure 3.

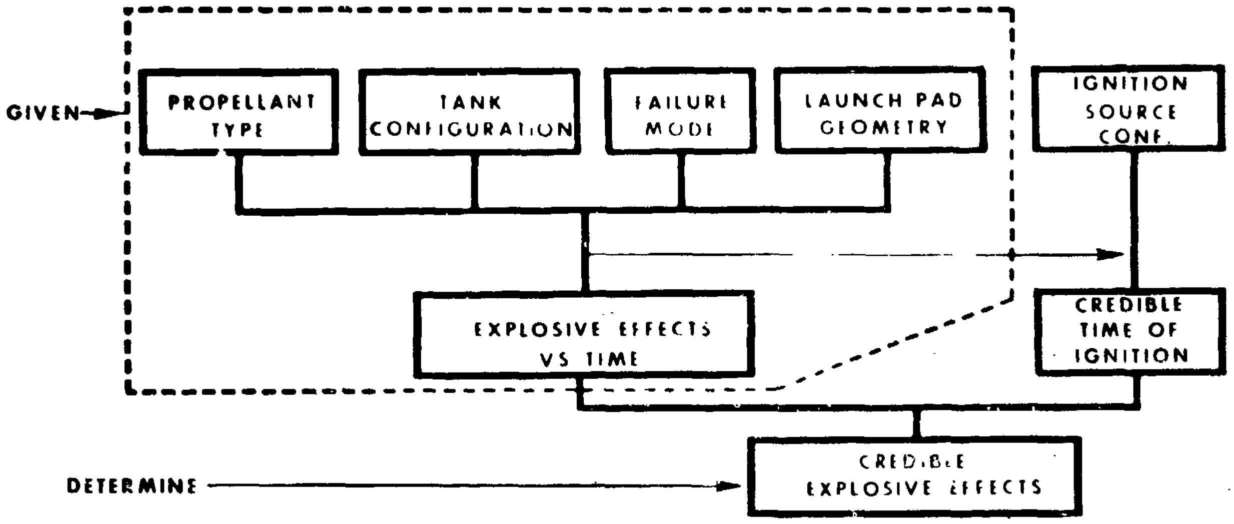


Figure 1. THE PROBLEM

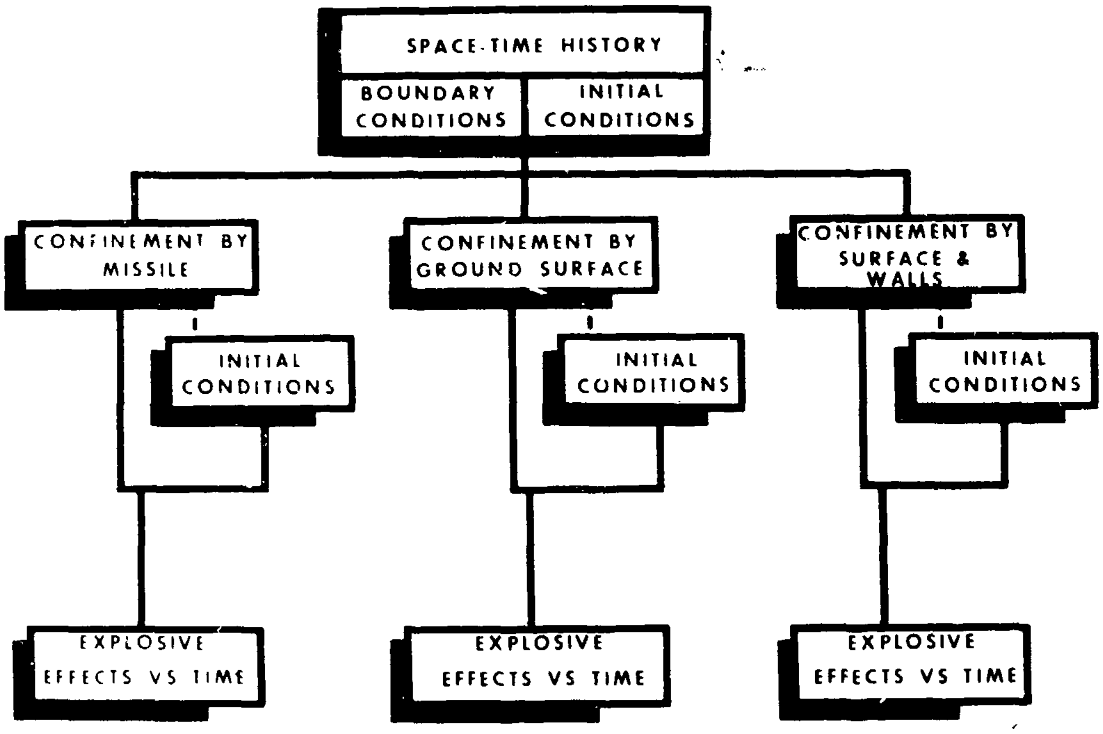


Figure 2. GENERALIZATION OF BASIC PARAMETERS

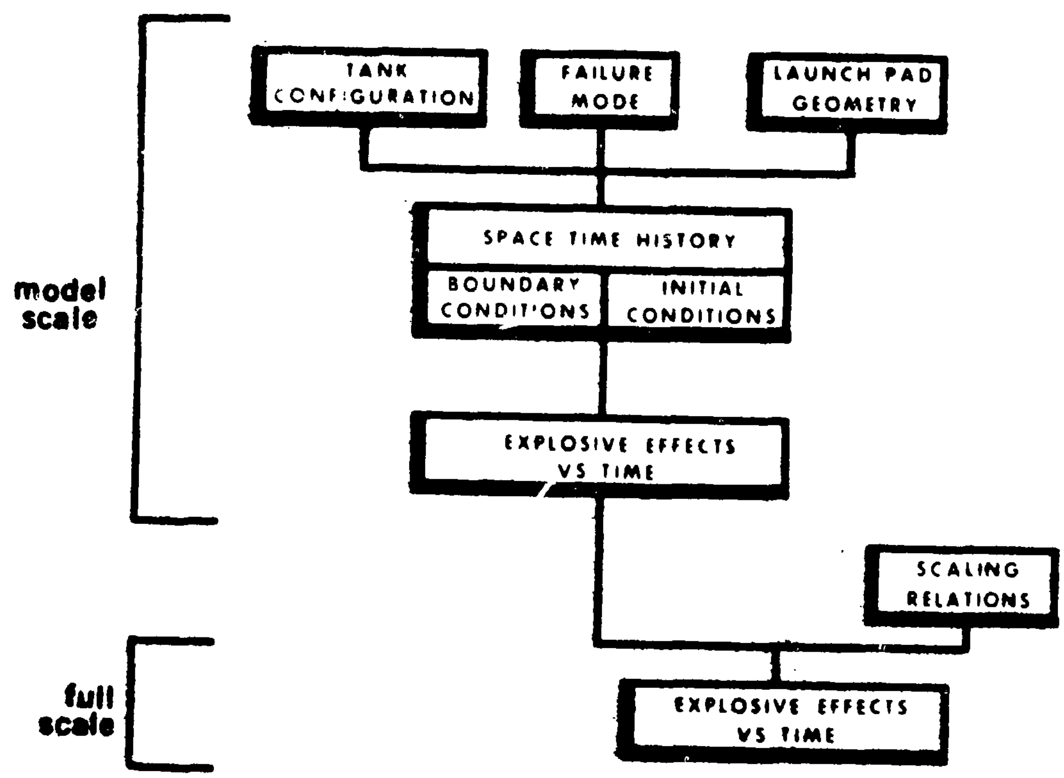


Figure 3. GENERAL TEST APPROACH
(For a Specified Propellant Combination)

Further descriptions of the three basic boundary conditions and the specific ranges in values of their initial condition parameters, considered of importance for each, are given in the following sections.

Confinement-By-The-Missile

In this case an internal failure is assumed to occur, and one propellant falls down into the other. The position and velocity distributions of the lower propellant at the moment of first contact are fairly well specified, since it is assumed to be in its original configuration and to have zero velocity. Those of the upper propellant, however, may have a large range of values, depending on how full the tanks are and how large an opening is created between them. If a relatively small opening is produced, the L/D ratio of the top propellant will be effectively very much greater than that of the bottom one, and its total weight (entering into the mixing at an early enough stage to be a matter of concern) will be much smaller than that for the bottom one. In addition, the top propellant will have an initial velocity given by the fluid head in the top tank and the pressure differential between the two tanks. As the opening between the tanks becomes enlarged, the L/D ratio and effective weight of the upper propellant more nearly approach the values they originally had in the missile. In addition, at the time the opening between the tanks is the full cross section of the original tank, the velocity would reach the value given by the acceleration of gravity through the distance of the ullage space in the lower tank, provided there was no pressure difference between the two tanks.

In the case where the opening between the tanks is significantly less than the full cross section of the missile, the different initial L/D values for each propellant can be treated by assuming that the L/D ratio refers to the overall missile geometry and by defining a D_o/D_t ratio, where D_o is the opening diameter and D_t the missile diameter.

Duration of the tank confinement case is limited to the time that the propellants remain confined by the walls of the missile. This time is determined by the strength of the tankage, the rate of vaporization of the cryogenic materials, the initial pressure in the tanks, and the initial ullage space.

The parameters considered to be of primary interest for this case and the ranges in values are as follows:

- Propellant Type: Two cases: LO_2/RP-1 and LO_2/LH_2

- Propellant Weight: 200-lb scale (selection of configurations for testing at larger scales will be made at conclusion of 200-lb tests)

- L/D Ratio: Two values: 5:1 and 1.8:1 (selected to span the range of credible missile geometries)

- D_o/D_t Ratio: Two values: 1:1 and 0.45:1

- Time of Ignition: Three values (to be selected later)

- Type of Ignition: Two cases: Detonator and squib

Figure 4 shows the test configuration used to provide the parameter variation needed for this test condition.

Confinement-By-The-Ground Surface

This test series is designed to investigate all cases in which massive rupture of the missile occurs, both propellants are released from the tanks, and initial contact and mixing take place on the ground surface.

A relatively large range in initial conditions is appropriate for this boundary condition because of the large variety of credible failure modes. Certain parameter selections and suggested number of levels are quite similar to those for the previous case, although specific values may not be identical. These include: Propellant type, weight and orientation, and time of ignition.

The major problem for this case is in establishing the appropriate L/D and velocity conditions. This is complicated because, theoretically, each of the two propellant masses may have a different L/D and magnitude and direction of flow. Thus, there really are six parameters, and if each were permitted to take on two values, 64 different combinations would be obtained. Fortunately, certain of these combinations seem so unlikely, they can be neglected.

The two sets of test conditions selected for the majority of testing in this general category are given below.

Vertical Propellant Flow Test Condition

In this case the propellants are initially contained in cylindrical tanks one on top of the other. The tanks are dropped from various

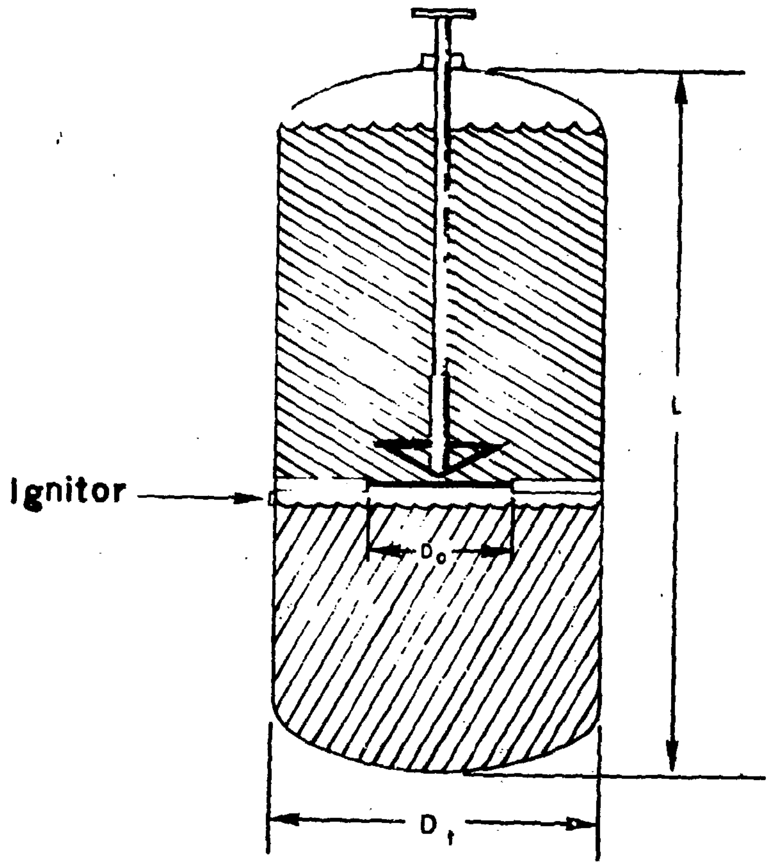


Figure 4. CONFINEMENT BY THE MISSILE TEST CONFIGURATION

heights (to provide the desired range in impact velocity) onto a breaker which rips open the thin aluminum foil tank bottoms. The tanks are stopped (above the ground), as soon as the bottoms are ripped open, by a rigid frame and the propellants are allowed to spill onto the ground surface.

The parameters of importance for this flow condition and the initially selected ranges in value are as follows:

- Propellant Type: Two cases - LO_2/RP-1 and LO_2/LH_2
- Propellant Length-to-Diameter Ratio (L/D): Two values - 5:1 and 1.8:1
- Propellant Orientation: Two cases - normal missile configuration and reversed
- Propellant Velocity at Impact: Two cases - Low $\simeq$ 15-20 ft/sec and High $\simeq$ 70-80 ft/sec
- Time of Ignition: Three values - two of which have been identified; these are "T_1", when the interface impacts on the ground surface, and "T_2", when all the propellants have reached the ground surface. The third time will be picked after completion of the first group of tests.

The test arrangement and the propellant orientations, at times T -1 and T -2, are schematically shown in Figure 5.

Horizontal Propellant Flow Test Condition

In this case the propellants are again initially contained in cylindrical tanks with thin foil bottoms; however, the tanks are not initially at the same height nor are they dropped simultaneously. The lower tank is positioned as near the ground surface as possible and still permit rupture of the bottom on dropping and clean spilling of the propellant on the ground surface (this drop height is about three ft.). The upper tank is dropped from various heights up to 100 ft to provide the desired impact velocity. The time sequence of drop is controlled so that the bottom propellant will have spread to a controlled diameter by the time the top propellant impacts on the ground surface. The parameters of primary concern for this flow direction case and the initially selected ranges in values are given below.

- Propellant Type: Two cases - LO_2/RP-1 and LO_2/LH_2

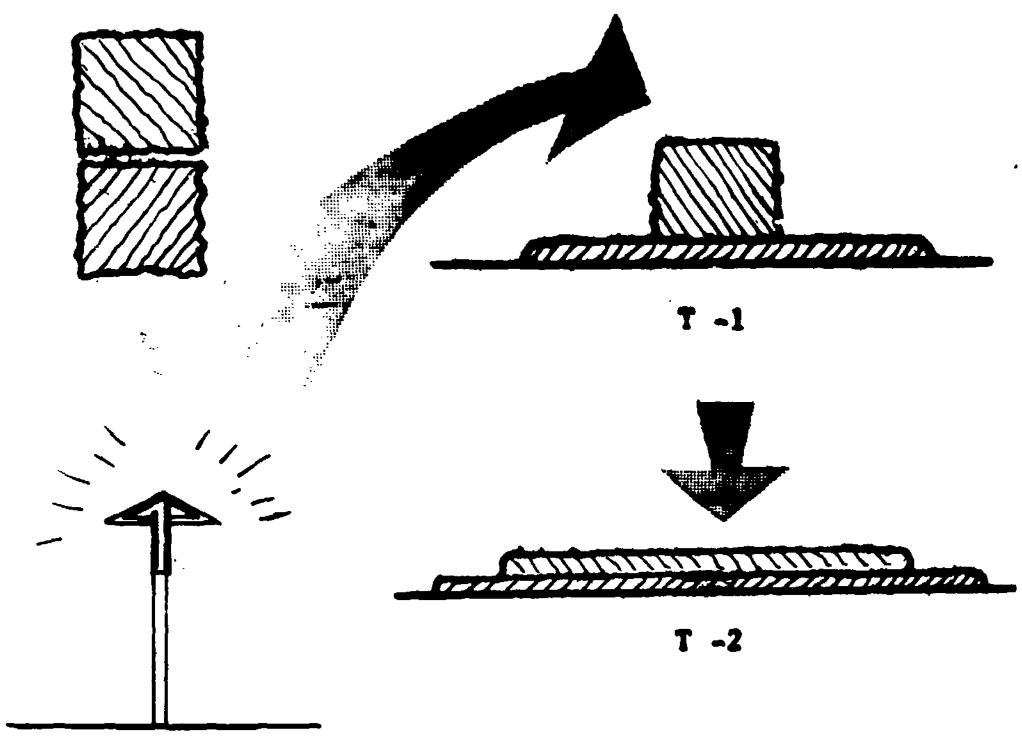


Figure 5. CONFINEMENT-BY-THE-GROUND SURFACE TEST CONDITION WITH VERTICAL PROPELLANT FLOW

- **Propellant Orientation:** One case - Normal missile configuration

- **Velocity:** Two values, Low, 10 - 20 ft/sec; High, 60 - 80 ft/sec

- **Pool Diameter:** Two values

- **Time of Ignition:** Three values

The two diameters of the bottom propellant planned are:

1. D-1. The minimum diameter of pool which can be easily obtained and still assure that all the propellant will have arrived on the ground surface.

2. D-2. The maximum diameter of pool that can be obtained and still assure that the flow of the propellant will be of uniform diameter. As fluid spreads out over a flat surface, it will maintain a circular shape until some finite depth is achieved. Then, due to surface irregularity, boundary layer, and other effects, the outer edge of the pool becomes irregular and fingers of fluid are formed. The maximum pool diameter value to be used for these tests will be limited to the one at which the pool is still circular in shape. The depth of the fluid in this large-diameter pool will be of the order of 0.1 inches.

The two initially identified ignition times are: Time T -1, when the top propellant has all arrived at the ground surface and has spread to the minimum pool diameter, D-1, of the bottom propellant; and Time T -2, when the top propellant has spread to a diameter equal to the maximum pool diameter, D-2, of the bottom propellant.

Thus, for tests in which the bottom propellant has the minimum diameter D-1, at T -1 the top propellant will have spread to approximately the same diameter pool as the bottom propellant and at T -2, to a diameter of about twice that of the bottom propellant. For tests in which the bottom propellant has the maximum diameter D-2, at T -1 the top propellant will have spread to approximately one-half the diameter of the bottom propellant and at T -2, to approximately the same diameter as the bottom propellant.

The relative positions of the fluids at the planned ignition times are schematically shown in Figure 6.

D-1
IGNITION TIME T -1

D-1

IGNITION TIME T -2

D-2

IGNITION TIME T -1

D-2

IGNITION TIME T -2

Figure 6. RELATIVE POSITIONS OF FLUIDS AT PLANNED IGNITION TIMES

Confinement-By-The-Ground Surface and Vertical Walls

In general, the ranges in initial conditions appropriate for this boundary condition are the same as those for the previous one (Confinement-by-the-ground surface). Assuming that the vertical walls are cylindrical, that the axis of the cylinder is concentric with that of the propellants, and that the walls are high enough to confine all the propellants, then the only additional parameter necessary to define this boundary condition is the diameter of the cylinder (D_c).

Two general credible cases of confinement by vertical walls are: (1) that resulting from a silo geometry and (2) that resulting from a shallow depression in a flat pad. The silo geometry would give the closest confinement; and based on typical silo geometries, a reasonable minimum wall diameter would be about five times the missile diameter. The range of credible values for the shallow depression might extend from as low as that for the silo to values two to three times this value.

Until the propellants reach the walls, mixing for the various initial conditions should be identical to that for the same initial conditions with the previous boundary condition (confinement-by-the-ground surface alone). Thus, the ignition delay times of interest are all greater than the time for the propellants to reach the walls. If it should turn out, for certain initial conditions, that most of the propellant mixing occurs prior to this time, then detailed study of this case for those initial conditions will not be necessary. Accordingly, final selection of the desired test conditions for this case will be deferred until the results from the tests with confinement-by-the-ground surface alone case have been analyzed.

Section 3

INSTRUMENTATION SYSTEM

This section describes the blast and thermal instrumentation systems used for the main portion of the PYRO test series being conducted at the AFRPL (Refer to AFRPL-TR-65-144 for detailed description of the instrumentation system (Ref. 1).

Blast

To provide adequate documentation of the explosive characteristics of propellant explosions, it is desirable to measure the pertinent blast characteristics as a function of both distance and azimuth. To provide this capability, the blast gauges were placed on three radial lines passing through ground zero and oriented 120 degrees with respect to each other.

The basic blast gauge system consists of overpressure sensors on each line at five radii for each propellant weight. Since the peak overpressure decreases approximately as the negative 1.8 power of the distance over the pressure range of primary concern, 1 to 100 psi, it was convenient to radially space the stations at distances differing by a factor of approximately 1.8. This results in pressures differing by a factor of 2.5 from station to station, or a total difference in pressure over five stations of a factor of about 40. This arrangement not only provides a reasonable spacing of stations by virtue of the pressure, but also permits use of most of the same stations when the propellant weight used in the testing is increased. The planned propellant weights are 200, 1000, and 25,000 lb. Since the pressure depends on the ratio of the distance to the cube root of the charge weight and since the pressure decreased approximately as the negative 1.8 power of the distance, the pressure at a given distance will vary approximately as the 0.6 power of the charge weight, i.e., it will increase by a factor of about 2.5 with an increase of charge weight by a factor of 5. Since this is the same as the difference in pressure from station to station, the same pressure range can be covered for a change in propellant weight by a factor of 5 by dropping the closest station and adding one new station at a distance of approximately 1.8 times the distance of the last station.

Since a variety of explosive yields were expected for each scale of testing, an intermediate yield level of 10 percent was selected for establishing the specific station location.

To supplement the basic overpressure measurement system, the following additional measurements are being obtained in the majority of tests.

- Two overpressure - time measurements as close to the explosion as practical

- Four measurements of stagnation pressure, spanning the range from near ground zero to the 32 psi level.

The layout for the blast measurement system at the AFRPL is given in Table I and Figure 7. Figure 8 is a photograph showing the configuration of a typical sensor station used to obtain overpressure and stagnation pressure measurements.

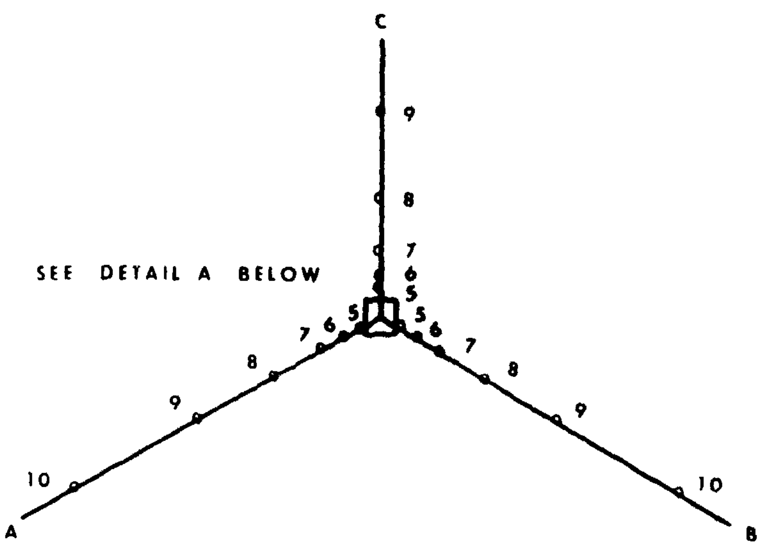
TABLE I

SUMMARY OF BLAST INSTRUMENTATION

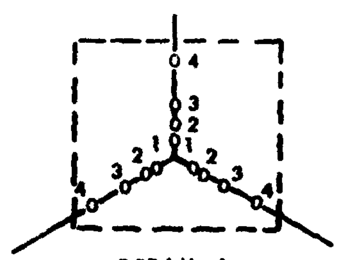
No.	Gauge Line	Nominal Distance (Ft)	Propellant Weight 200 Lb P_s*	200 Lb P_o**	1,000 Lb P_s	1,000 Lb P_o	25,000 Lb P_s	25,000 Lb P_o
I	A	2.8						
	B			X				
	C							
II	A		X	X				
	B	4.5				X		
	C							
III	A				X	X		
	B	7.5	X	X				
	C			X				
IV	A							
	B	13		X	X	X		X
	C		X	X		X		
V	A			X			X	X
	B	23		X		X		
	C			X	X	X		
VI	A			X		X		
	B	38		X		X	X	X
	C			X		X		X
VII	A			X		X		
	B	67		X		X		X
	C			X		X	X	X
VIII	A					X		X
	B	117				X		X
	C					X		X
IX	A							X
	B	200						X
	C							X
X	A							X
	B	335						X
	C							X

* P_s = head-on-oriented stagnation pressure sensor

** P_o = side-on-oriented overpressure sensor



DISTANCE FROM GZ (ft)	
1	2.8
2	4.5
3	7.5
4	13.0
5	23.0
6	38.0
7	67.0
8	117.0
9	200.0
10	335.0



DETAIL A

Figure 7. INSTRUMENTATION LAYOUT

Figure 8. TYPICAL OVERPRESSURE AND STAGNATION PRESSURE MEASUREMENT STATION

Thermal

The objective of the thermal measurement system is to obtain sufficient data to allow prediction of heat fluxes into any material exposed either inside or outside the fireball. Because of the uncertain nature and severity of the environment provided by the propellant explosions, a variety of thermal instruments are being used in an effort to provide the desired documentation.

Inside the fireball, both radiant and convective heat fluxes are of interest, while only radiant fluxes are of interest outside the fireball.

The specific thermal measurements being made include:

1. Radiant flux external to the fireball with radiometers

2. Fireball surface temperatures with a photo-record pyrometer

3. Fireball dimensions with high-speed photography

4. Radiant flux within the fireball with radiometers

5. Front-surface temperatures of copper and stainless steel slabs within the fireball by means of Delta Couples (Estimates of forced convection heat transfer can be obtained from this data and that given in 4 above.)

6. Gas temperature within the fireball with microminiature thermocouple probes

A summary of the thermal instrumentation used in the PYRO test series by test weight is presented in Table II. Figure 7 gives the sensor locations. Figure 9 is a photograph of thermal Station III-A.

Section 4

SATURN S-IV TEST

A controlled failure test of a full-scale Saturn S-IV stage without engine, loaded with approximately 92000 lb of LO_2/LH_2, was conducted during July 1965. Failure was induced by rapidly creating an 18 inch diameter hole in the intertank bulkhead with a cutter ram.

TABLE II

SUMMARY OF THERMAL INSTRUMENTATION

No.	Gauge Line	Dist. (ft)	Propellant Weight 200 lb	1,000 lb	25,000 lb
I	A B C	2.8			
II	A B C	4.5			
III	A B C	7.5			
IV	A B C	13	T_c T_s R_s T_c T_s R_s TR_c	T_c T_c T_s T_s R_s R_s	
V	A B C	23		T_c T_s R_s T_c T_s R_s TR_c	
VI	A B C	38			T_c T_c T_s T_s R_s R_s
VII	A B C	67	R_p R_p		T_c T_s R_s T_c T_s R_s TR_c
VIII	A B C	117	R_p	R_p R_p	
IX	A B C	200		R_p	
X	A B C	335			R_p R_p

T_c = copper-plate surface thermocouple
T_s = stainless-steel-plate surface thermocouple
TR_c = head-on, rounded copper-plate thermocouple
R_p = radiometer (PYRO type)
R_s = radiometer (launch-pad surveillance type)

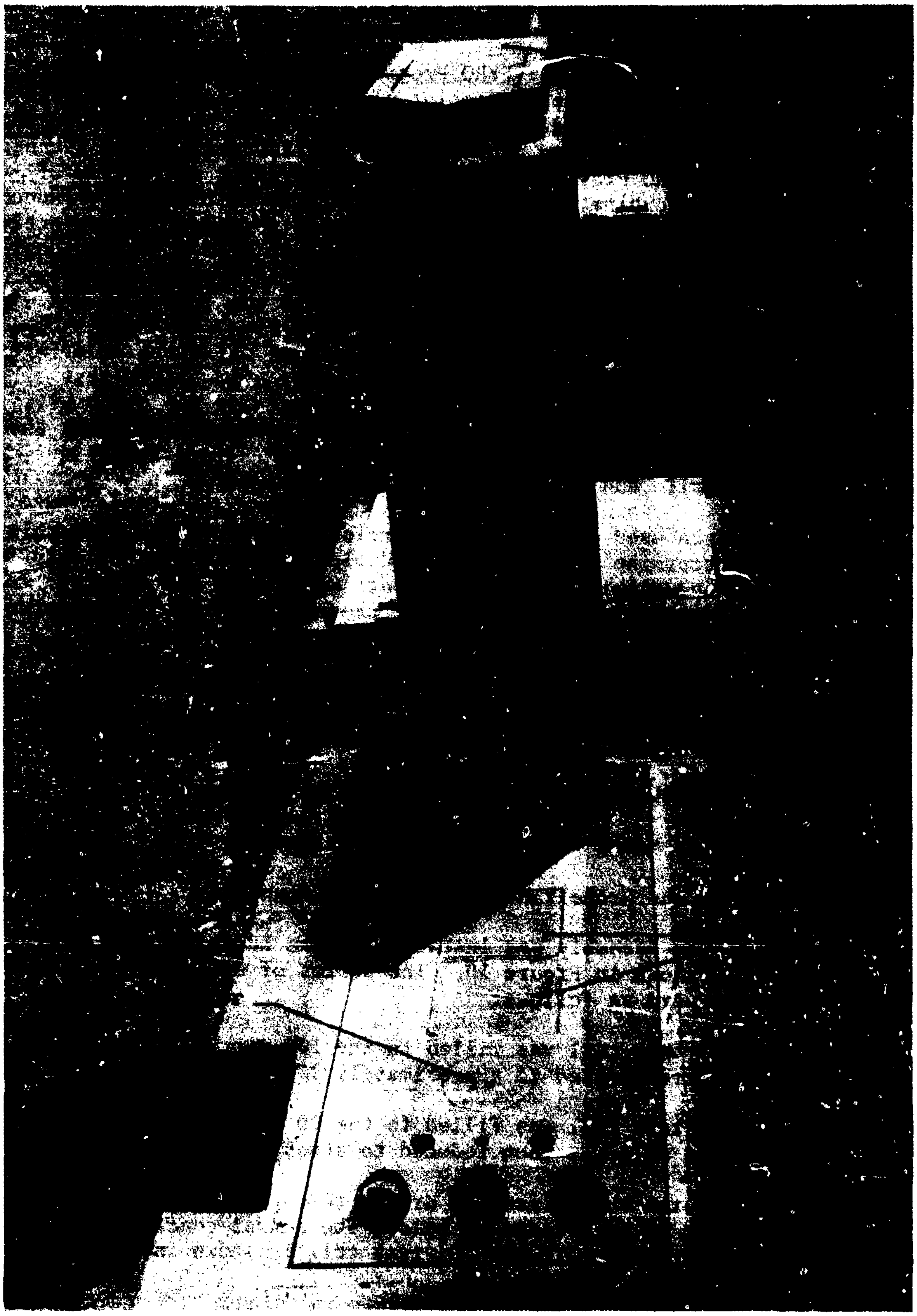


Figure 9 ELEVATED THERMAL SENSOR MOUNT AT STATION III-A

In regard to the overall PYRO Program, the objective of this test was to obtain a full-scale data point of the blast and thermal hazard from the propellant combination LO_2/LH_2. This data point, in conjunction with the data obtained from the many smaller scale tests planned in the overall PYRO Program, will be used to predict the hazard of this propellant combination in either the static test stand or launch geometry. There was also, however, a somewhat more specific objective to this test. At that time, there was an urgent need for additional data to re-evaluate the explosive potential of this propellant combination in static test stand operations.

This last objective restricted the choice of a failure mode for this particular test to one entirely consistent with static test stand operation. Because this was a single test and one which will be used to help formulate safety criteria, it was desirable that the failure mode chosen yield the "maximum credible" hazard for this particular missile and particular test stand geometry.

The approach used to choose the particular failure mode for this test was to determine the possible credible failure modes, briefly review these and eliminate those elements which tend to minimize the yield. Of the remaining elements, those that tended to maximize the yield were used to construct a composite failure mode.

To meet the requirements imposed by the maximum credible failure mode, test procedures and hardware were developed to meet the following objectives:

1. Rupture the common bulkhead

2. Forcibly bring the two propellants together

3. Ignite the propellant mixture at a known time

A cutter ram assembly was installed in the LO_2 tank cell as schematically shown in Figure 10. The series of events which preceded the explosion were as follows:

- The LH_2 tank cell was filled to the 100 percent level and the tank cell was pressurized to approximately 20 psig.

- The LO_2 tank cell was filled to the 90 percent level and the pressure in the cell was then reduced to atmospheric pressure.

- At T -0 the cutter ram was driven through the intertank bulkhead opening an 18 inch diameter hole. The actual configuration of the cutter ram position in the LO_2 tank cell is shown in Figure 11.

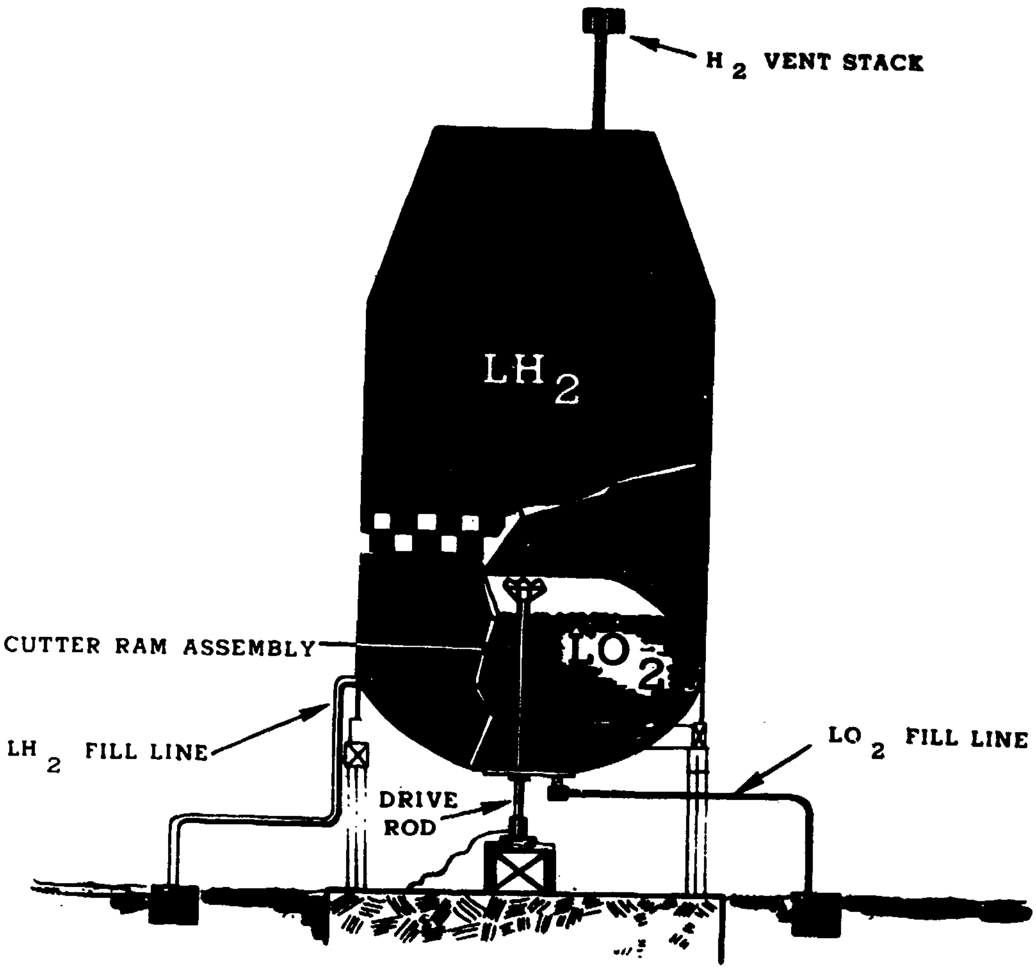


Figure 10 SCHEMATIC OF CONFIGURATION USED FOR THE SATURN S-IV TEST

Figure 11 POSITION OF CUTTER RAM ASSEMBLY IN THE SATURN S-IV LO_2 TANK CELL JUST PRIOR TO FINAL ASSEMBLY

Since the explosive yield was expected to increase as the time available for propellant mixing increased, it was desirable from the viewpoint of obtaining the maximum credible explosive yield that ignition occur at the latest credible time during the failure process.

This time was selected as the time that the tankage would rupture due to pressure buildup in the tank from LH_2 vaporization. Accordingly, it was planned to let the failure sequence proceed by itself after initially opening the hole in the intertank bulkhead until the first sign of tankage rupture, at which time two shaped charges would be manually initiated. Self ignition occurred, however, well before this time, approximately 205 msec after the cutter ram penetrated the bulkhead.

Although it is possible that a time as short as this could be the maximum credible ignition time, there is insufficient evidence available at present to justify this position. Accordingly, it is concluded that the explosive yield value obtained from this particular test should not be considered as the maximum credible value but only as a typical value.

Figure 12 is a photograph showing the Saturn S-IV just prior to the test. Figure 13 is a series of photographs showing the fireball sequence that resulted from the explosion. Figure 14 shows the post test damage.

Saturn S-IV Blast Results

The peak overpressure data are plotted in Figure 15 as a function of ground distance. The explosive yields computed from these data as well as those obtained from the positive-phase impulse data are presented in Table III. It can be seen that there is a tendency for both the pressure and impulse yields to increase with distance at the closer stations. These trends are generally similar to those observed with the results from the 200-lb low yield LO_2/LH_2 confinement-by-the-missile tests.

Saturn S-IV Thermal Results

Thermal data obtained from the S-IV test included radiant flux both inside and outside the fireball, surface temperature measurements in copper and stainless steel slabs within the fireball, thermocouple measurements within the fireball, and fireball dimensions as a function of time. Typical examples of each type of data are shown in Figures 16 through 20.

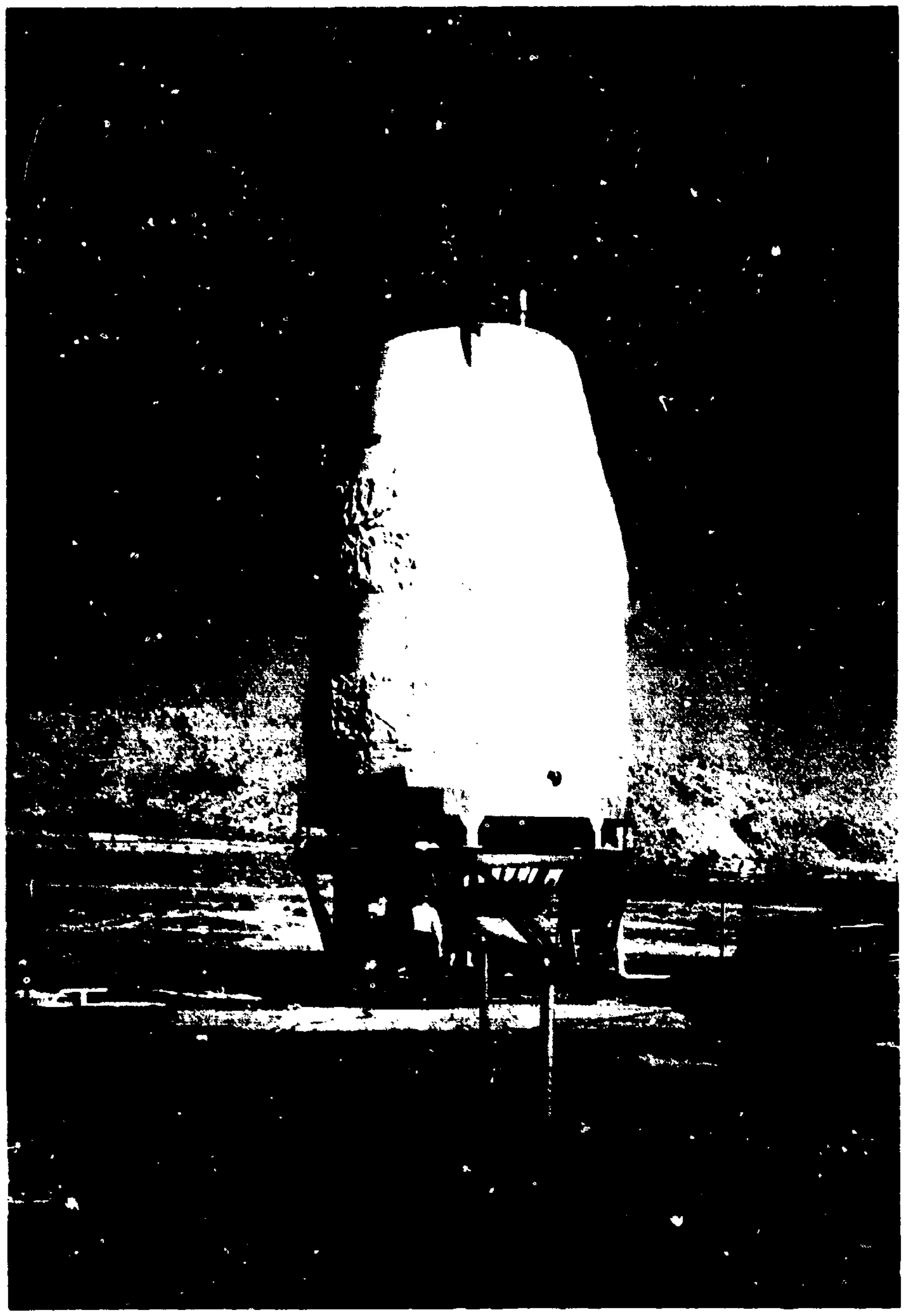


Figure 12 SATURN S-IV BEFORE TEST

T +205 (Ignition)

Figure 13 - SATURN S-IV TEST, FIREBALL SEQUENCE

Figure 14 SATURN S-IV POST TEST DAMAGE

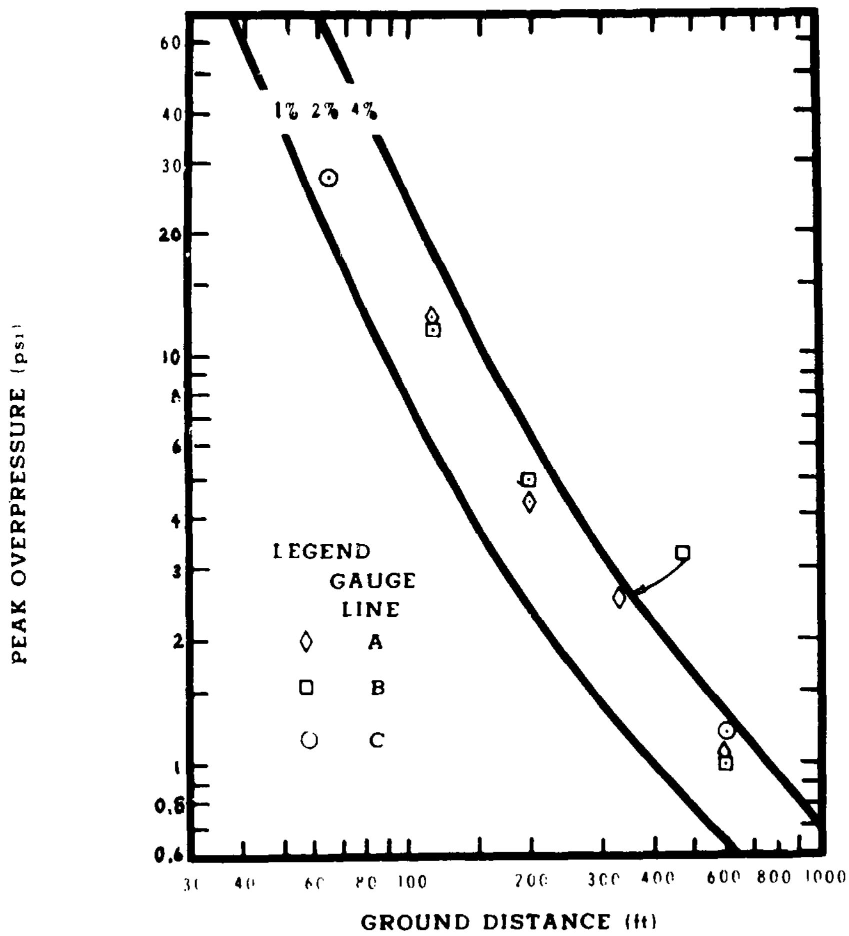


Figure 15 PEAK OVERPRESSURE VS GROUND DISTANCE FOR SATURN S-IV TEST

TABLE III

SATURN S-IV EXPLOSIVE YIELDS

	Yield (%)*	
Distance (ft)	Pressure	Impulse
38	1.5	6.0
67	1.5	4.2
117	2.5	5.8
200	2.4	-
335	3.5	6.8
600	2.9	6.6

* Relative to TNT surface burst.

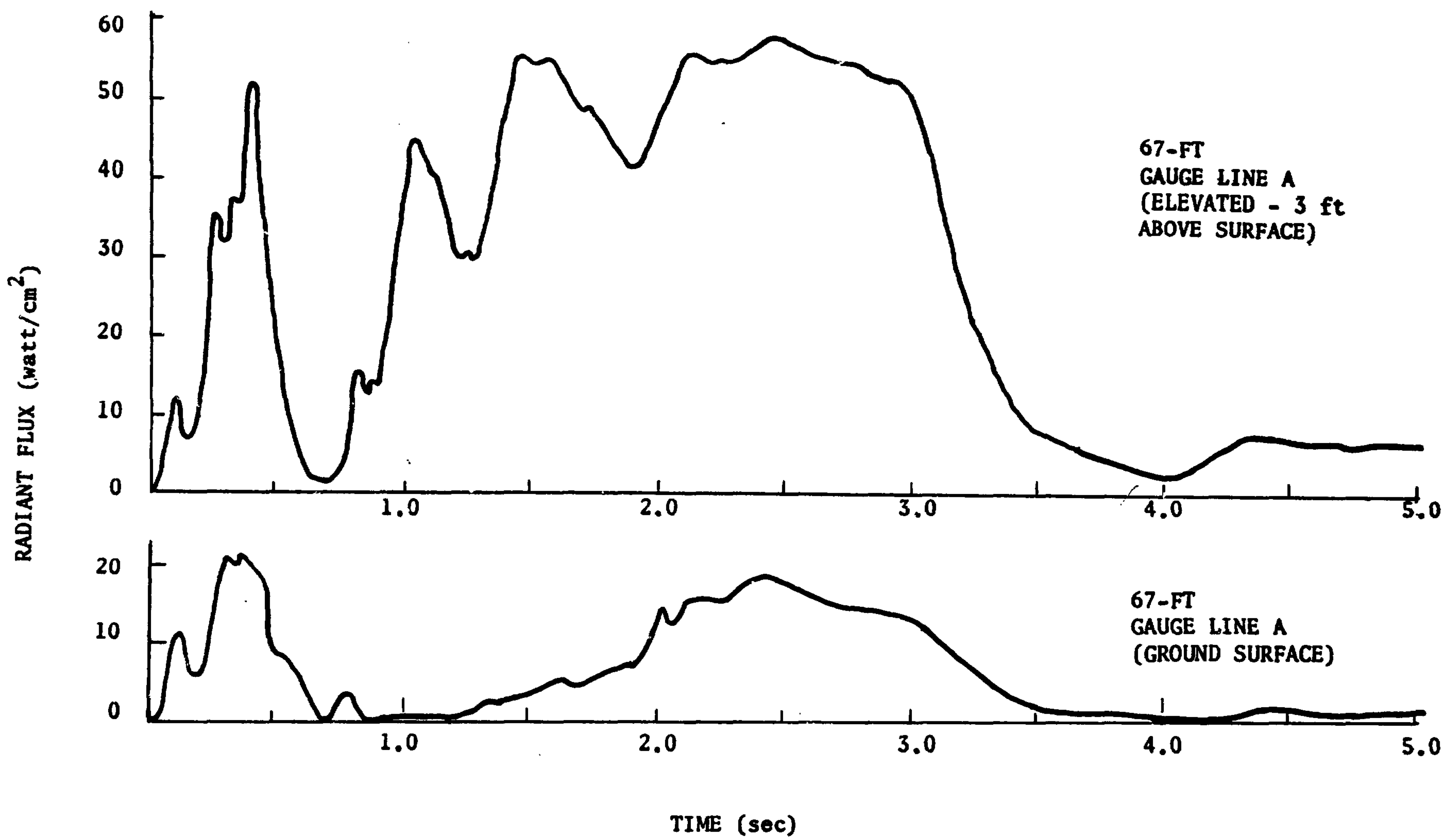


Figure 16 RADIANT FLUX WITHIN THE S-IV FIREBALL

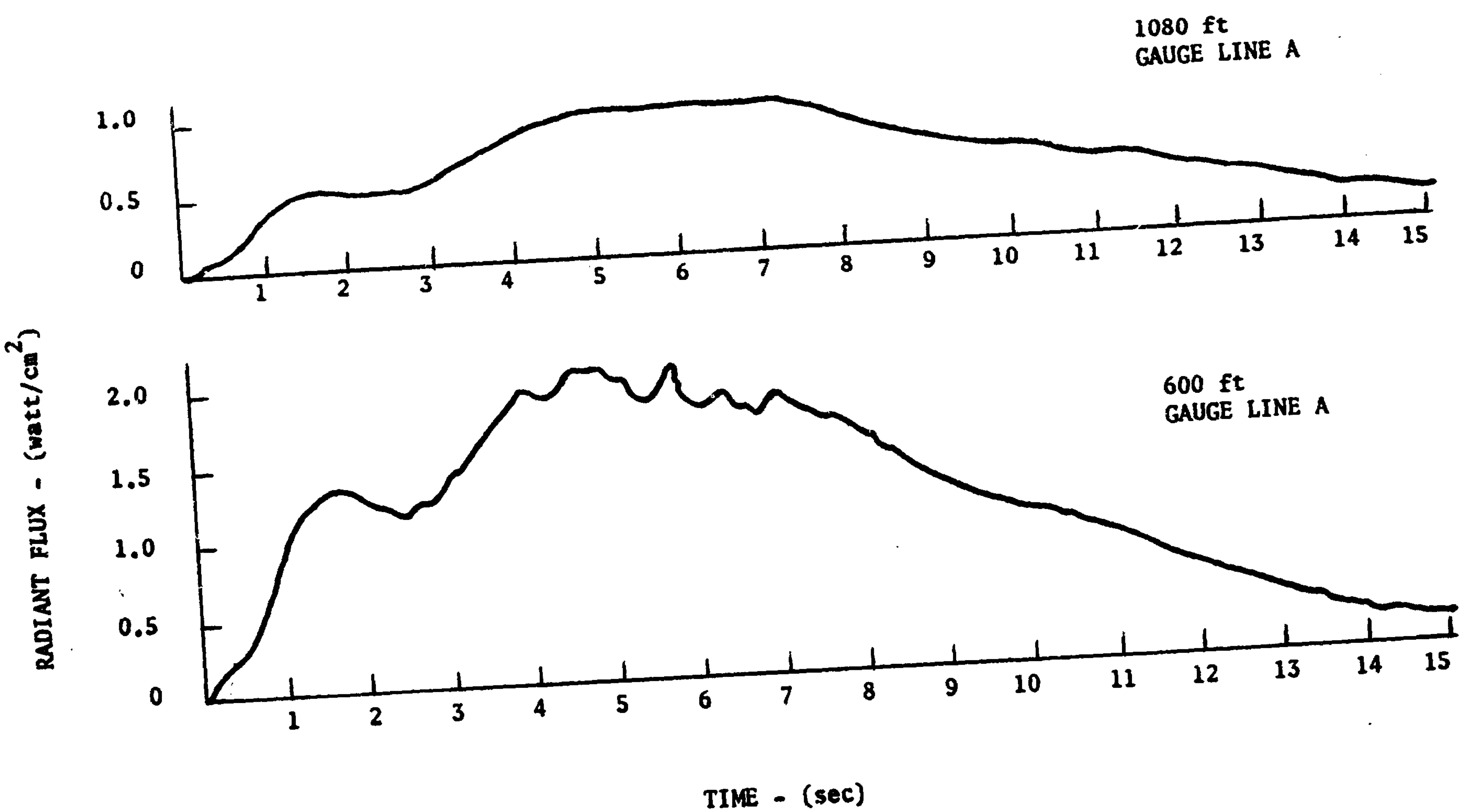


Figure 17 RADIANT FLUX EXTERNAL TO THE FIREBALL FROM THE S-IV TEST

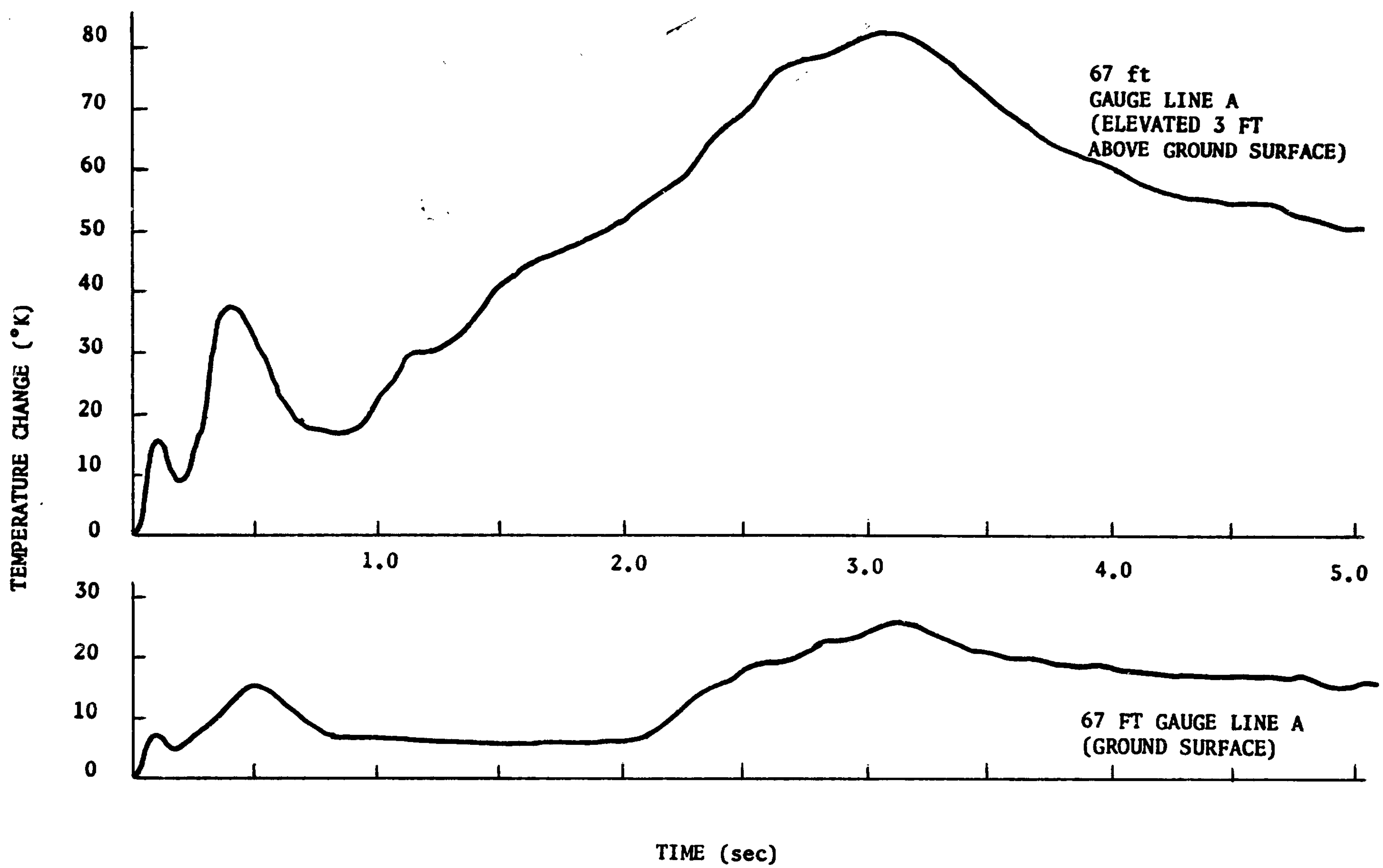


Figure 18 SURFACE TEMPERATURE OF STAINLESS STEEL PLATES WITHIN THE S-IV FIREBALL

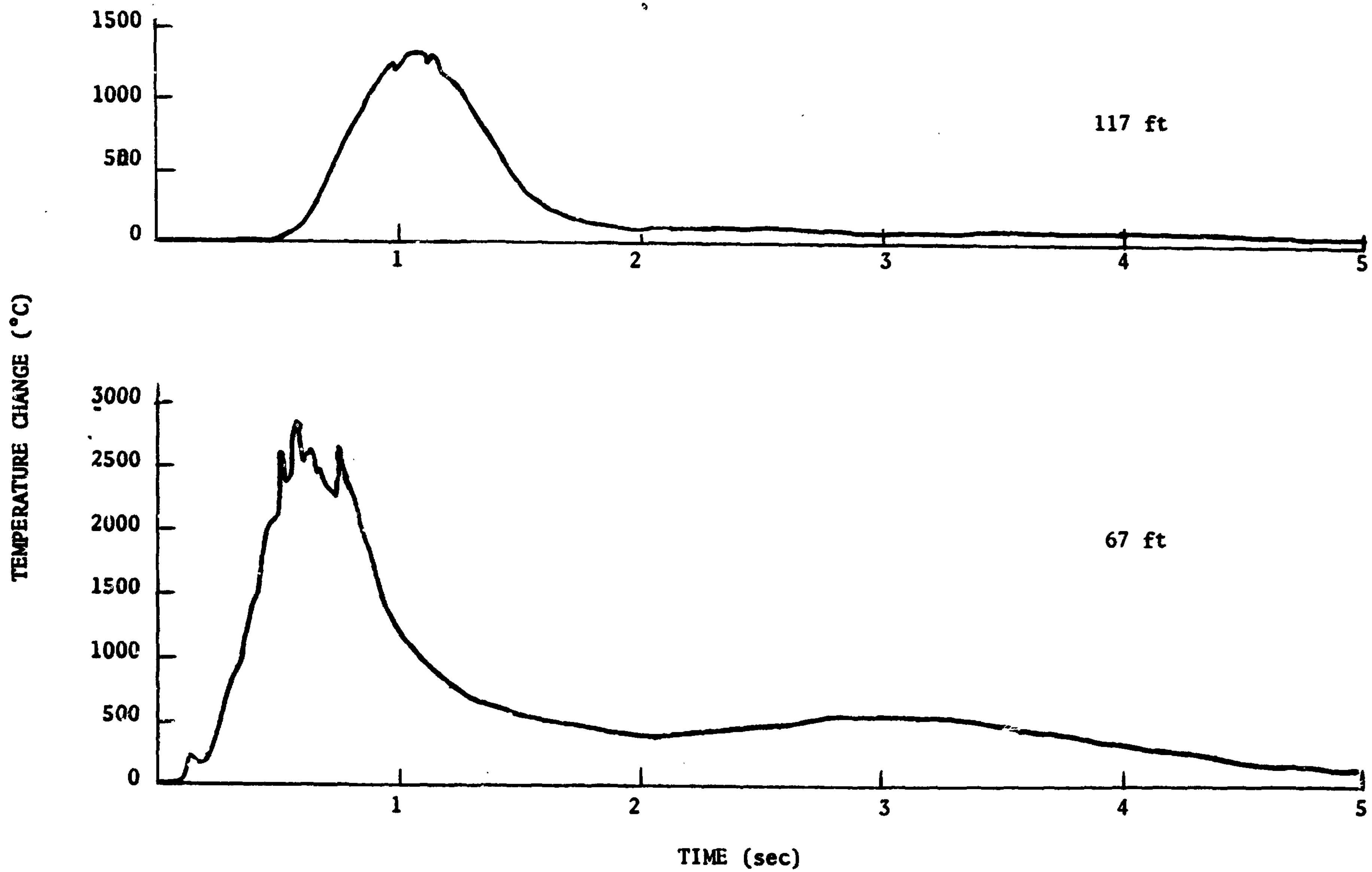


Figure 19 TEMPERATURES FROM THERMOCOUPLE PROBES WITHIN THE S-IV FIREBALL

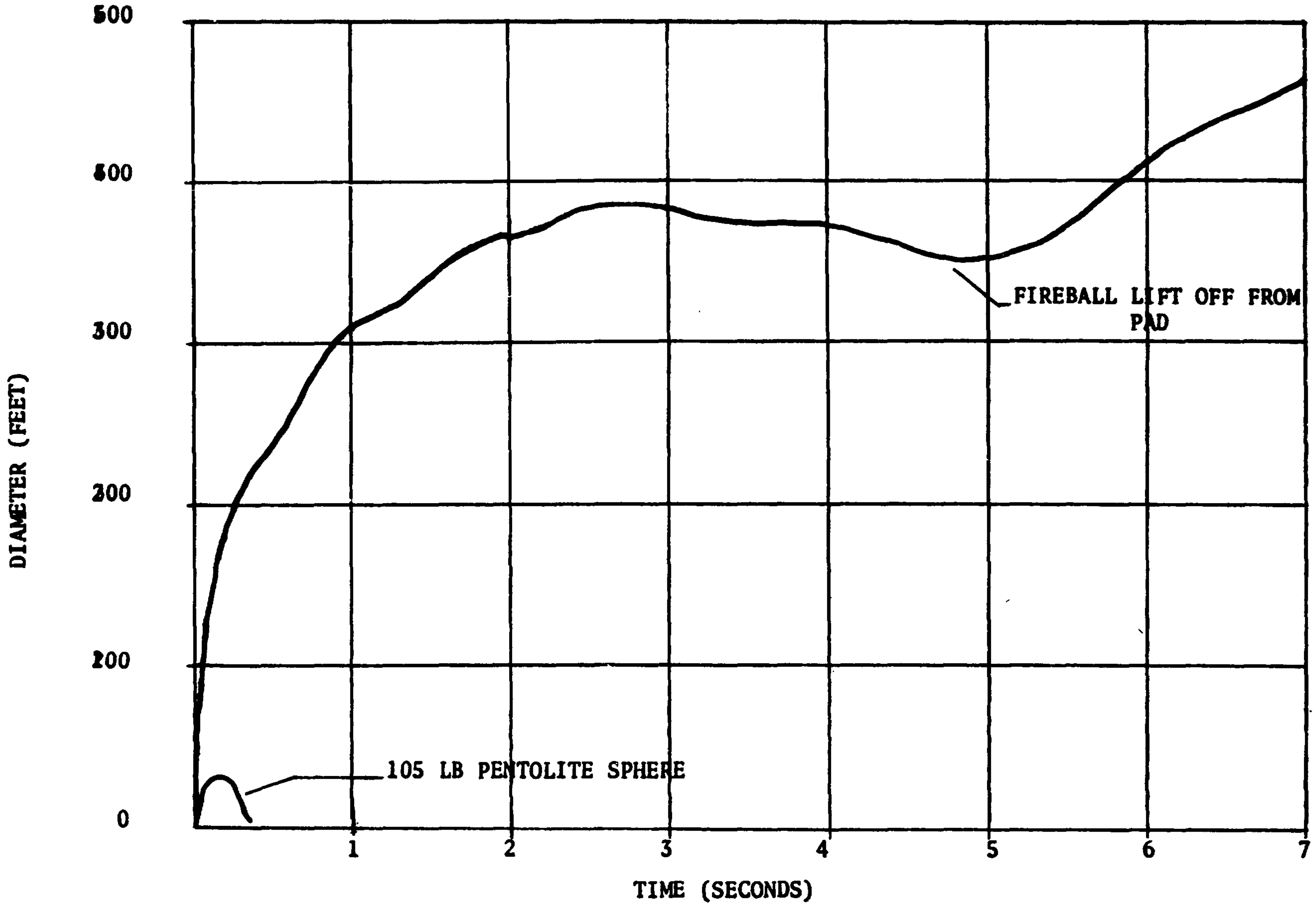


Figure 20 SATURN S-IV TEST, HORIZONTAL FIREBALL HISTROY

It is interesting to note that the radiant flux measurements within the fireball (Figure 16) decrease nearly to zero, after an initial rise, before returning to approximately the same magnitude as the initial maximum. In order to account for this result, i.e., for the radiant flux to approach zero when the radiometers are surrounded by a fireball, it is necessary to postulate that there was a layer adjacent to the radiometers which shielded them from the fireball radiation and which itself did not radiate appreciably.

It seems most likely that this layer consisted of water vapor which was condensed out of the air or out of the reaction products by unreacted liquid oxygen or cold gaseous oxygen.* At the closer distances, liquid oxygen or its vapor may have contributed to this layer. The presence of large quantities of liquid oxygen or cold gaseous oxygen on the ground surface would be expected because of the failure and explosion process. The main portion of the mixed propellants contributing to the initial explosion must have been near the LO_2 - LH_2 interface, so that the explosion would tend to separate the propellants and to disperse the unreacted oxygen (in liquid or gaseous state) over the ground surface. The low ($\approx 5\%$) explosive yield suggests that a large fraction of the original LO_2 was available for such dispersal. The presence of large amounts of frost on the surface surrounding ground zero after the test tends to confirm this general behavior pattern.

At the 67 - and 117 - ft distances, it is presumed that the mid-pulse flux decrease was caused by the arrival of the cold layer and that it dissipated in about one second, permitting the radiometers to see the fireball again. At the 38 ft station, where there was no indication of a significant second pulse, it is presumed that the cold layer, being thicker, persisted for the duration of the fireball.

Comparison of the data from the ground and elevated stations at the 67 - ft distance indicates that the shielding effect extended to the elevated station, although it was not as pronounced in that the flux recovered more rapidly.

* Consideration was also given to the possibility that the observed thermal behavior was due to a dust layer near the ground surface. Although it is difficult to rule this possibility out completely, it seems unlikely that it could have caused the type of transient behavior observed on the radiometers, Delta Couples and thermocouple probes.

The results from the other thermal instrumentation are generally consistent with the postulated sequence of events. Preliminary estimates of the heat transfer required to result in temperature rises such as those obtained from Delta Couple plates (Figure 18) indicate that the plates received an appreciable portion of their heat from radiation; and from the shapes of their traces, it can be seen that they received little heat during the period when the radiometers were not receiving a significant amount of flux.

The temperature probe data (Figure 19) also showed a large temperature decrease at the presumed time of LO_2 arrival; however, in contrast to the radiometer and Delta Couple data, the temperatures did not subsequently increase very much. This is not surprising since the temperature probes are not very sensitive to radiation, but rather tend to follow the temperature of the ambient gas, which even after the LO_2 and water vapor have evaporated, is likely to be much cooler than the main part of the fireball. Lifting of the fireball off the ground may have contributed to the low reading of the probes at later times.

The only thermal instruments which did not show any significant effects of the LO_2 layer were the radiometers which were mounted external to the fireball. Their traces (given in Figure 17) show a single pulse extending for the entire duration of the fireball. This also is not surprising since these instruments viewed the entire fireball, and even if a small portion of the fireball near the ground had been shielded, it would not have had any significant effect on the total radiation.

The overall heat transfer along the ground surface was lower than expected due to the presence of the cold layer. The elevated station indicated somewhat higher heat transfer levels, and it is possible that they were higher further off the ground.

Additional instrumentation is being installed to study the heat transfer levels at higher elevations.

Section 5

HIGH VELOCITY IMPACT TEST SERIES*

The original purpose of the high velocity impact test series was to determine the explosive yield of the hypergolic propellant combination under one of the two sets of conditions which were expected to maximize the explosive yield, i.e., nose-on impact of a vehicle at

high velocity on a hard and a soft ground surface. The scope of the impact program was later expanded to include a few tests with the cryogenic propellant combinations to provide comparative information on propellant type.

Experimental Arrangement

In these tests, the various propellant combinations were placed in thin-walled cylindrical aluminum tanks, accelerated on a sled track to high velocities (340 to 580 ft/sec) and allowed to impact into massive concrete targets. The majority of tests utilized targets of two types: a flat-wall target, which was selected to simulate impact into a rigid ground surface, in which no impact cratering would occur, and the deep-hole target, which simulated a soft ground surface, in which significant cratering would occur.**

In total, 20 tests utilizing the flat-wall and deep-hole targets were conducted, 14 with N_2O_4/50% UDMH - 50% N_2H_4, four with LO_2/RP-1, and two with LO_2/LH_2. Five of the hypergolic tests utilized 1000 lb propellant weight; the other nine hypergolic tests and all cryogenic tests utilized 200 lb propellant weight.

In addition to the propellant tests, 12 high explosive shots using 18 to 216 lb spherical pentolite charges were fired for calibration purposes.

The flat wall and deep hole target configurations used for these tests are shown in Figures 21 and 22, respectively. These targets were placed against a steel plate, which is backed up by a massive (approximately 144,000 lb) concrete block.

A sketch of the tank for the hypergolic propellant combination with dimensions for both the 200 lb and 1000 lb test articles is presented in Figure 23. In these tanks the N_2O_4 was placed in the forward compartment and impacted the target first. A sketch of the cryogenic tank design is shown in Figure 24. The LO_2 was in the forward compartment of the LO_2/RP-1 tanks and the LH_2 was in the forward compartment of the LO_2/LH_2 tanks.

The overall site geometry and instrumentation layout used for the test series is shown in Figure 25. The nominal measuring station distances noted in this figure varied somewhat from test to test, depending on the type of target being used and the fact that the massive concrete backup block was occasionally moved a small amount as a result of the test.

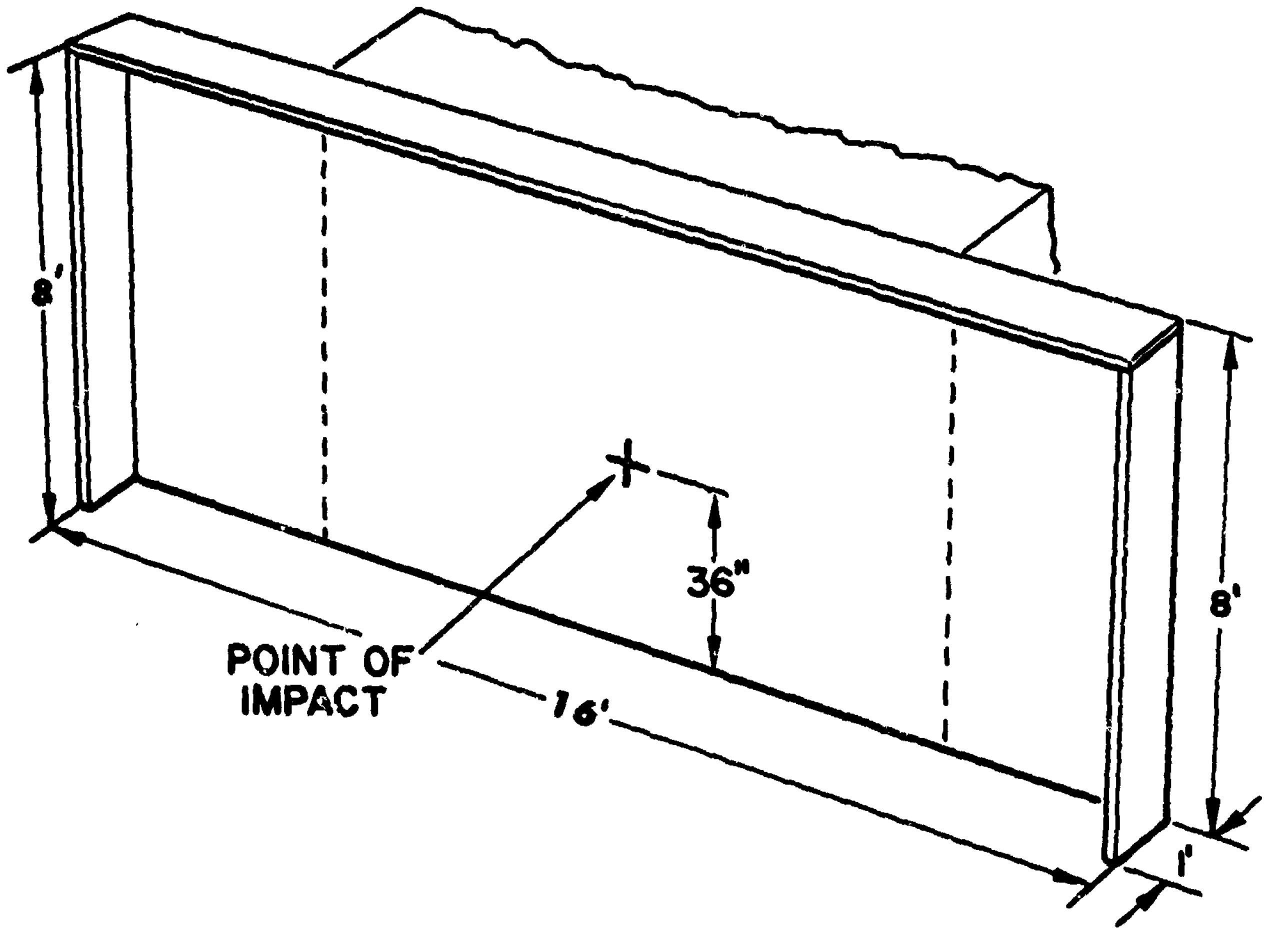
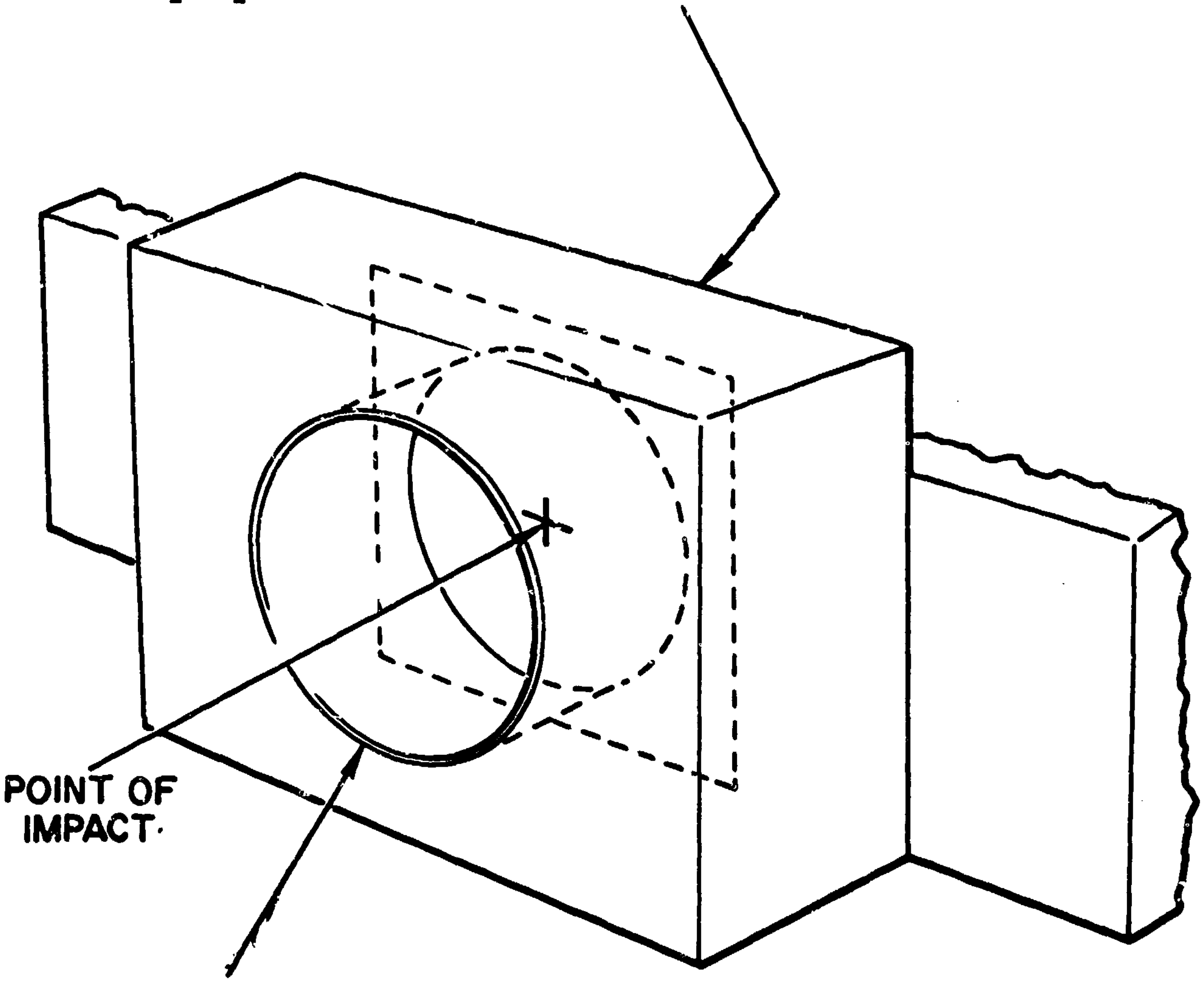


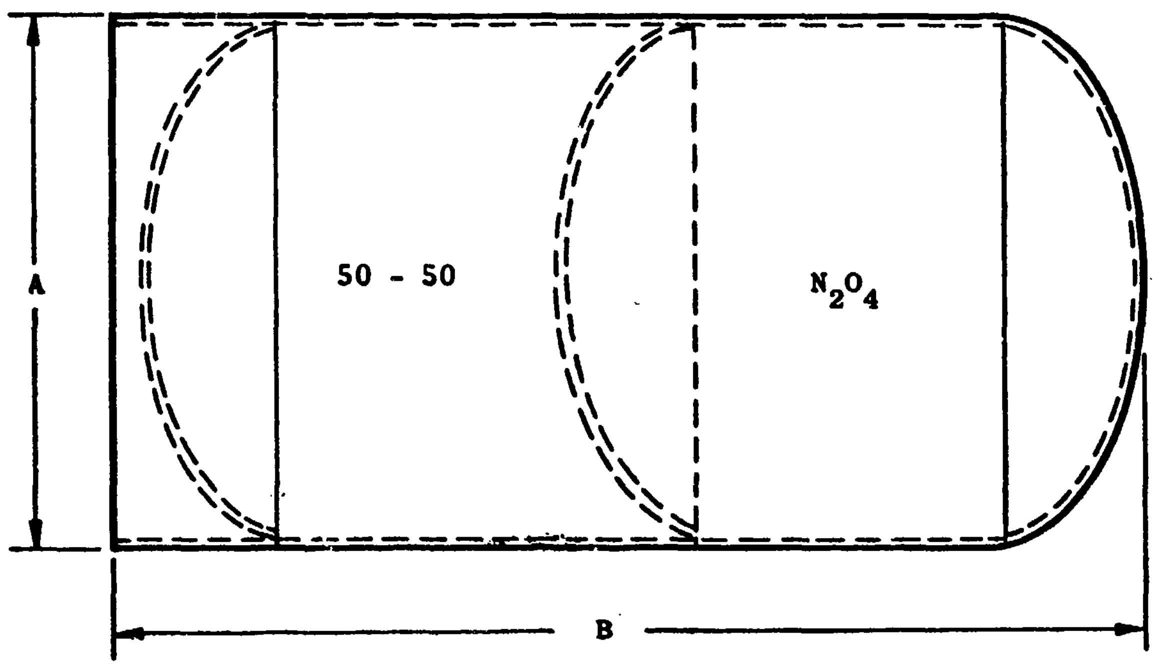
Figure 21 FLAT-WALL TARGET FOR HYPERGOLIC IMPACT TESTS

Hypergolic - 200-LB: 72 IN. WIDE X 72 IN. HIGH X 62 IN. DEEP
Hypergolic - 1,000 LB: 92 IN. WIDE X 87 IN. HIGH X 92 IN. DEEP
LO_2/RP-1 - 200 LB: 72 IN. WIDE X 72 IN. HIGH X 62 IN. DEEP
LO_2/LH_2 - 200 LB: 88 IN. WIDE X 85 IN. HIGH X 86 IN. DEEP



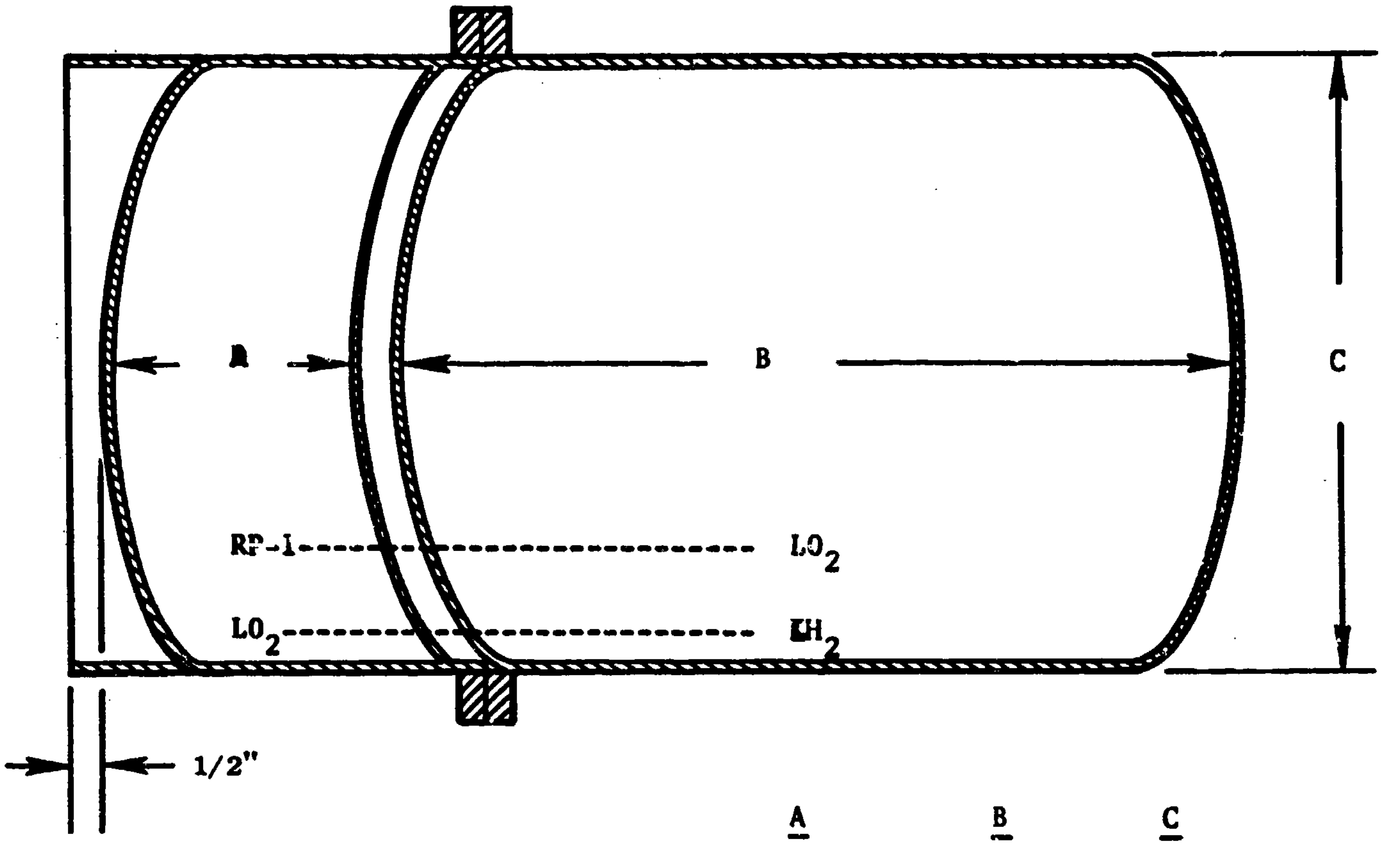
Hypergolic - 200 LB: 32 IN. DIA X 48 IN. DEEP
Hypergolic - 1,000 LB: 52 IN. DIA. X 78 IN. DEEP
LO_2/RP-1 - 200 LB: 32 IN. DIA. X 48 IN. DEEP
LO_2/LH_2 - 200 LB: 48 IN. DIA. X 78 IN. DEEP

Figure 22 DEEP-HOLE TARGET FOR HYPERGOLIC & CRYOGENIC IMPACT TESTS



	A	B
200 LB	16 IN.	26.75 IN.
1,000 LB	26.25 IN.	49.03 IN.

Figure 23 HYPERGOLIC IMPACT TANK



	A	B	C
LO_2/RP-1	10.5"	21.5"	16.0"
LO_2/LH_2	10.0"	36.4"	23.8"

Figure 24 200 LB CRYOGENIC IMPACT TANK

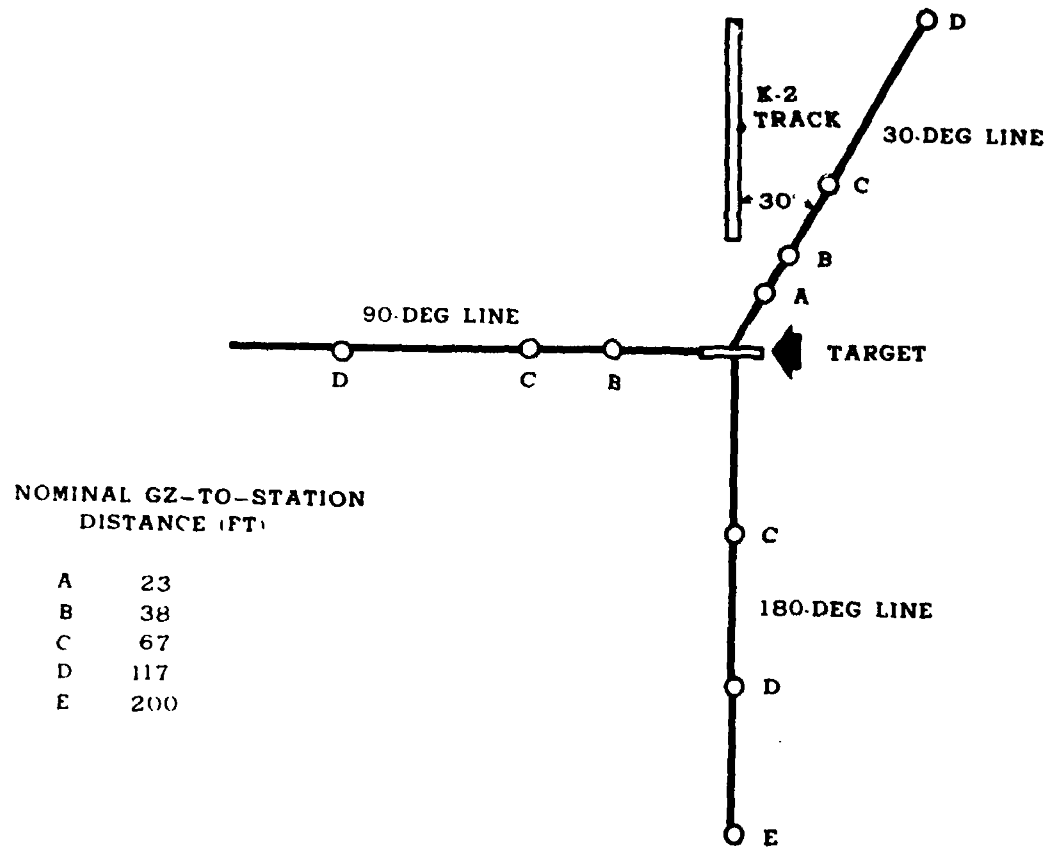


Figure 25 TEST SITE AND INSTRUMENTATION LAYOUT FOR IMPACT TESTS

The instrumentation layout shown in this figure was used for all the cryogenic tests and about one-half the hypergolic tests. For the remaining hypergolic tests, which were conducted in an earlier test series, a somewhat less extensive gauge layout was used. It consisted of the 30 degree line as shown in Figure 25, plus a line at 60 degrees to the track on the opposite side from the 30 degree line.

* These tests were carried out by the Naval Ordnance Test Station, China Lake, California

** A few tests were also run with a shallow hole target and a parallel wall target. The results from these tests tended to fall between those from the flat wall and deep hole targets, so that they are not discussed here.

Results

The terminal explosive yields obtained from these tests are given in Tables IV and V.

From an analysis of the data given in these tables, the following conclusions have been drawn:

1. The target geometry is significant, i.e., the deep hole target gives significantly higher yields than the flat wall target.

2. The yields from LO_2/LH_2 are significantly greater than those from the LO_2/RP-1 or from N_2O_4/50% UDMH - 50% N_2H_4.

3. There are no significant differences between the yields from LO_2/RP-1 and from N_2O_4/50% UDMH - 50% N_2H_4.

4. For the hypergolic propellant combination, the variation in impact velocity from approximately 340 to approximately 580 ft/sec did not significantly affect the yield; and there was a slight tendency for the yield to decrease with increasing propellant weight for the tests with the deep hole target. (The cryogenic propellant tests did not include variations in velocity or propellant weight).

5. The standard deviation for the hypergolic propellant, for a given test condition, is about 22 percent of the mean yield.

TABLE IV

EXPLOSIVE YIELDS FROM HYPERGOLIC IMPACT TESTS

Velocity Range	Scale (lb)	Explosive Yield (%) Target Geometry	
		Flat Wall	Deep Hole
High (~570 ft/sec)	200	13, 15	56, 37
	1000	15, 23	28, 34
Low (~ 340 ft/sec)	200	5	38
	1000	21	-

TABLE V

EXPLOSIVE YIELDS FROM CRYOGENIC IMPACT TESTS
(200 lb Propellant Weight)

Velocity Range	Propellant Type	Explosive Yield (%) Target Geometry	
		Flat Wall	Deep Hole
High (~520 ft/sec)	LO_2/RP-1	21 – 20	57 – 77
High (~580 ft/sec)	LO_2/LH_2	121	163

Section 6

DESCRIPTION OF OTHER TESTS

A brief description of the other tests being conducted under Project PYRO is presented in this section. These tests include approximately 90 - 200 lb LO_2/RP-1 and LO_2/LH_2 test articles to investigate the effects of the confinement-by-the-ground surface and the confinement-by-the-missile test conditions, described in Section 2; and also four 200 lb N_2O_4/50% UDMH - 50% N_2H_4 high drop tests. The results of these tests will be documented in the PYRO Program Final Report to be distributed during July 1967.

Figure 26 is a photograph of the 100 foot tower that provides the capability to conduct high and low drop tests. The tower tripod support structure is designed to withstand a 1,000 lb TNT explosion over ground zero. A remotely operated propellant transfer system, installed as an integral part of the tower structure, is used to fill the 200 lb and 1,000 lb test articles at the initial test height with any of the propellant combinations.

Confinement-By-The-Ground Surface Test Series

Figure 27 is a photograph of a typical 200 lb LO_2/LH_2 test article used for conducting the low drop confinement-by-the-ground surface tests with the vertical propellant flow mixing condition. The bottom of the LO_2 tank cell is elevated approximately 8.5 feet above the ground surface before the drop test is initiated. A similar test article configuration is used for conducting the high drop test series. Specifically, the test article is elevated to approximately 98 feet above the ground surface before the test is initiated. Ignition of the propellant mixture is remotely provided using primacord ordnance placed on the ground surface as shown in Figure 28. Ignition time delays used for this test condition are described in Section 2.

Figure 29 is a photograph of a typical 200 lb LO_2/RP-1 test article used for conducting the dual low drop confinement-by-the-ground surface tests with the horizontal propellant flow mixing condition. Drop heights for these test articles are altered for each test to provide the desired propellant mixing geometries described in Section 2. Figures 30 and 31 are photographs of the RP-1 and LO_2 tank cells.

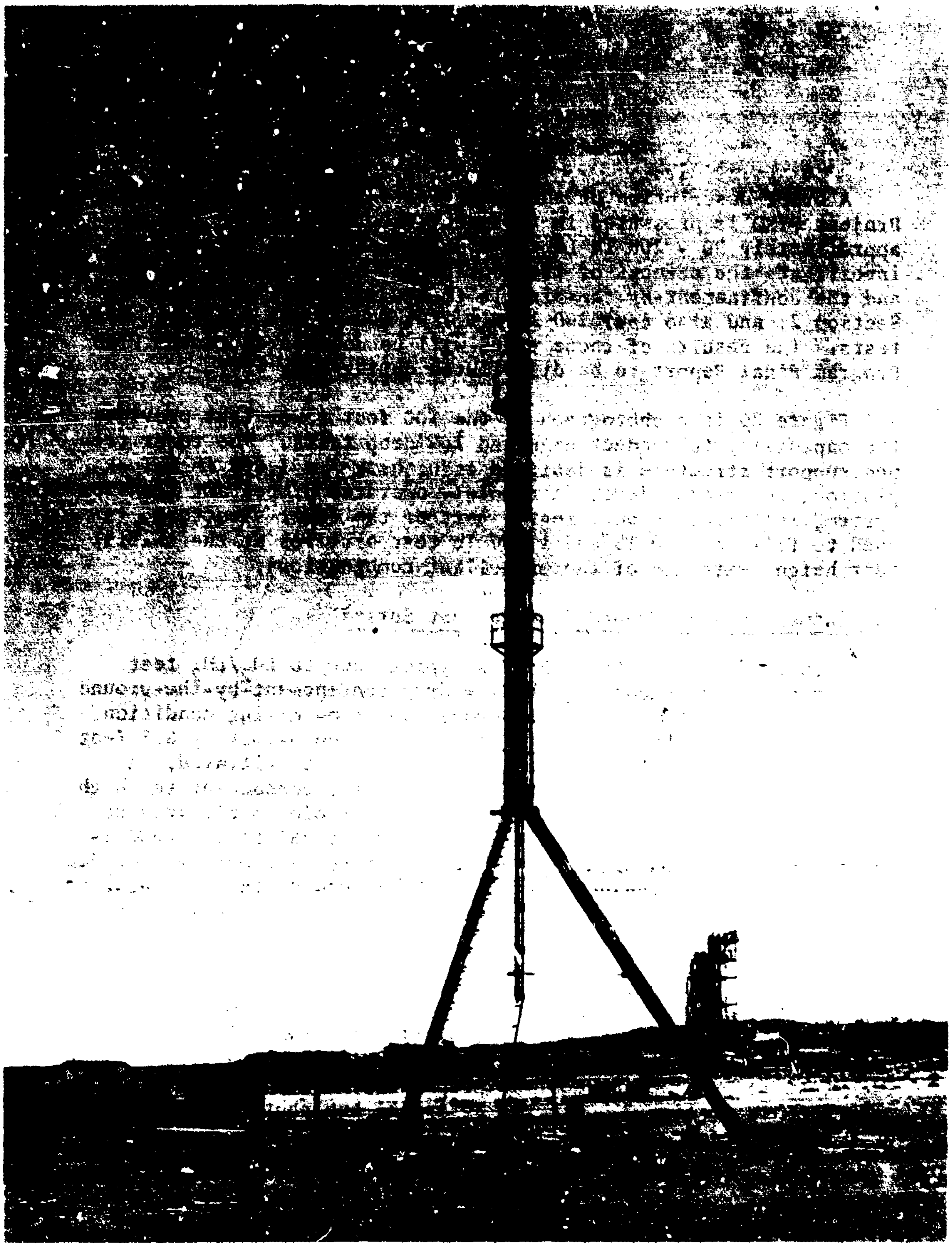


Figure 26 100 FT DROP TOWER USED FOR THE LOW & HIGH DROP PROPELLANT TEST SERIES

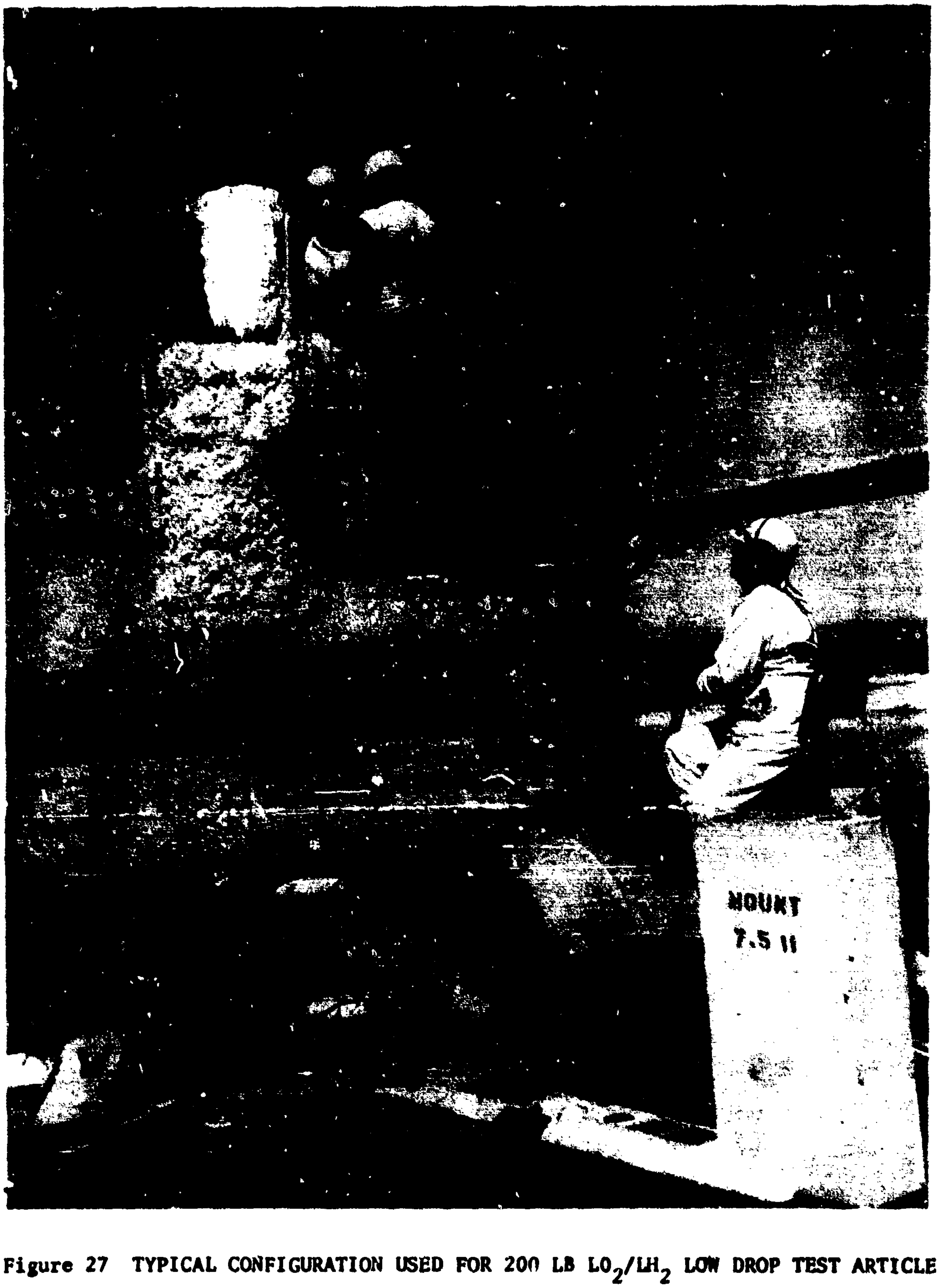


Figure 27 TYPICAL CONFIGURATION USED FOR 200 LB LO_2/LH_2 LOW DROP TEST ARTICLE

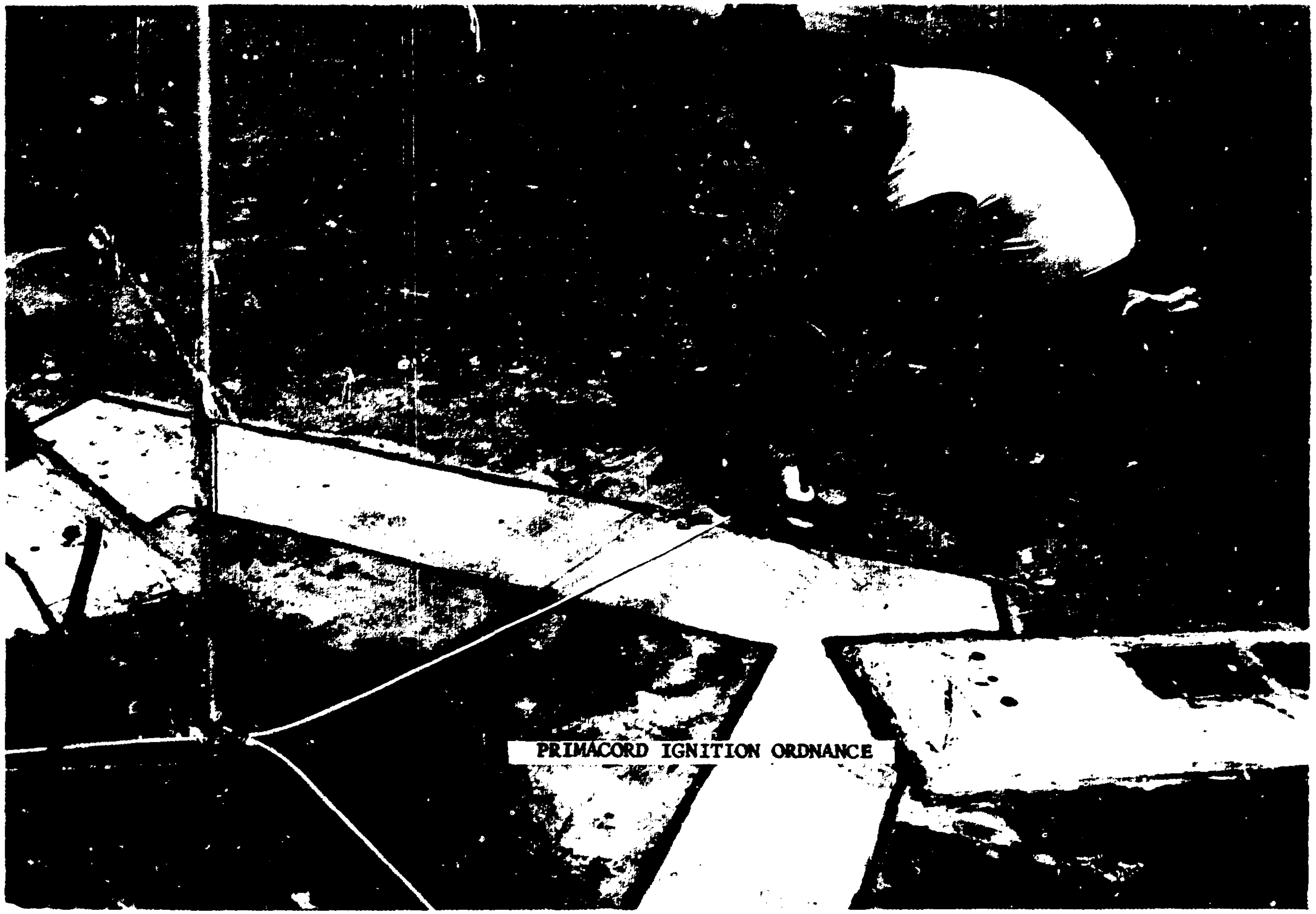


Figure 28 TYPICAL CONFIGURATION OF ORDNANCE IGNITER SOURCE

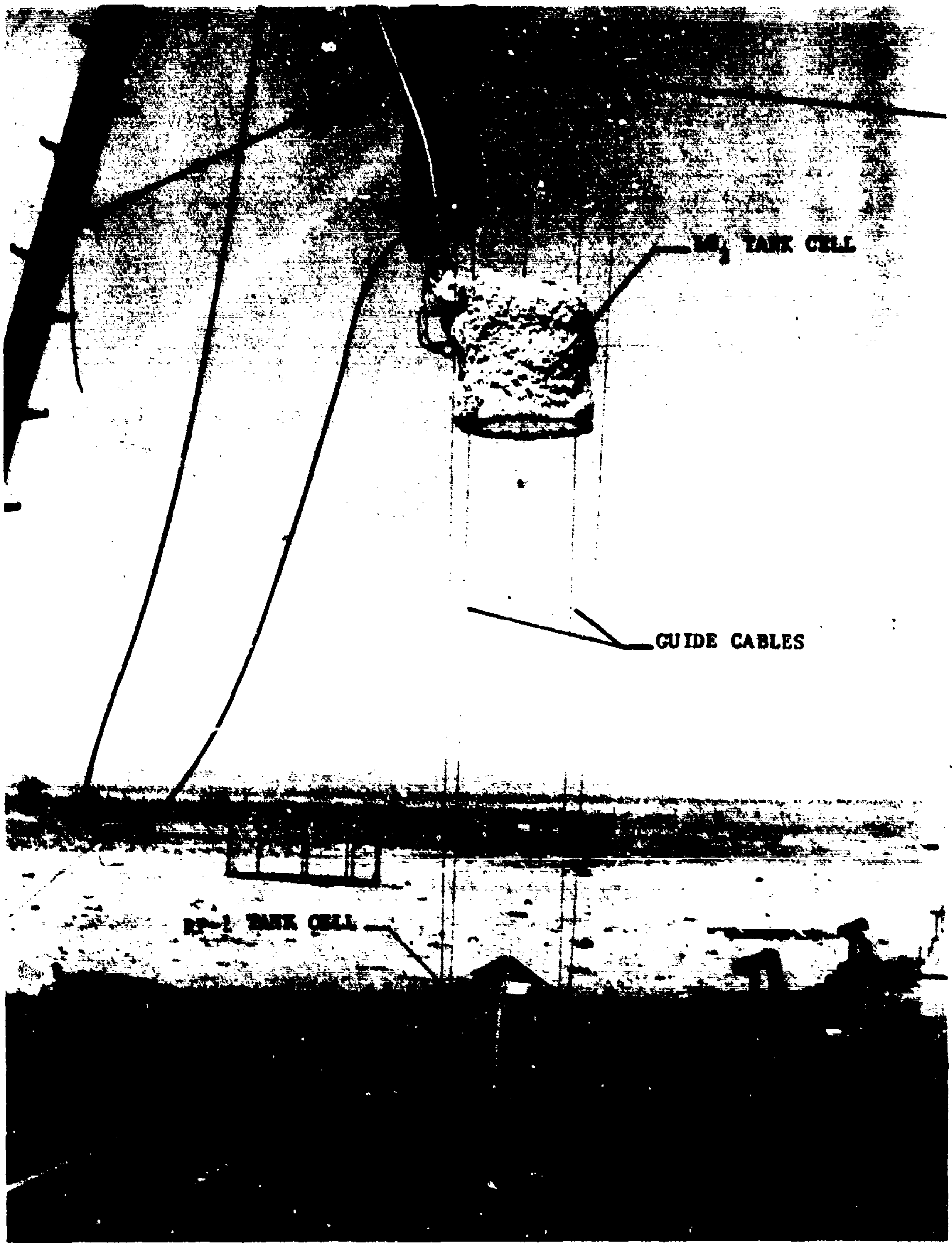


Figure 29 TYPICAL CONFIGURATION USED FOR 200 LB LO_2/RP-1 DUAL LOW DROP TEST ARTICLE, PROVIDES HORIZONTAL PROPELLANT FLOW MIXING CONDITION

Figure 30 TYPICAL CONFIGURATION OF RP-1 TANK CELL USED FOR 200 LB LO_2/RP-1 DUAL LOW DROP TEST ARTICLE

Figure 31 TYPICAL CONFIGURATION OF LO_2 TANK CELL USED FOR 200 LB LO_2/RP-1 DUAL LOW DROP TEST ARTICLE

Confinement-By-The-Missile Test Series

Figure 32 is a photograph of a typical 200 lb LO_2/LH_2 test article used for conducting the confinement-by-the-missile test condition described in Section 2. A typical test sequence using this test article is to fill the LO_2 and LH_2 tank cells, vent the LO_2 tank cell to atmospheric pressure and allow LH_2 tank cell pressure to build up to 20 psig, and then provide an opening in the tempered glass intertank bulkhead. The tempered glass membrane is removed using a breaker ram device driven by a 0.1 lb C-4 ordnance charge placed on the breaker ram pusher plate. An ordnance detonator cap is used to ignite the propellant mixture at the desired delay times. The test configuration used for the LO_2/RP-1 confinement-by-the-missile test condition is similar to the LO_2/LH_2 test article shown in this figure.

N_2O_4/50% UDMH - 50% N_2H_4 High Drop Tests

Figure 33 is a photograph of a typical 200 lb N_2O_4/50% UDMH - 50% N_2H_4 test article used for conducting 100 foot drop tests. This test condition is similar to the LO_2/RP-1 confinement-by-the-ground surface test article that provides a vertical propellant flow mixing condition. As noted in this figure, N_2O_4 is in the upper tank cell and 50% UDMH - 50% N_2H_4 is in the bottom tank cell. An aluminum baffle plate is provided on the test article to reduce the probability of a vapor phase hypergolic ignition of the two propellants during fill operations.

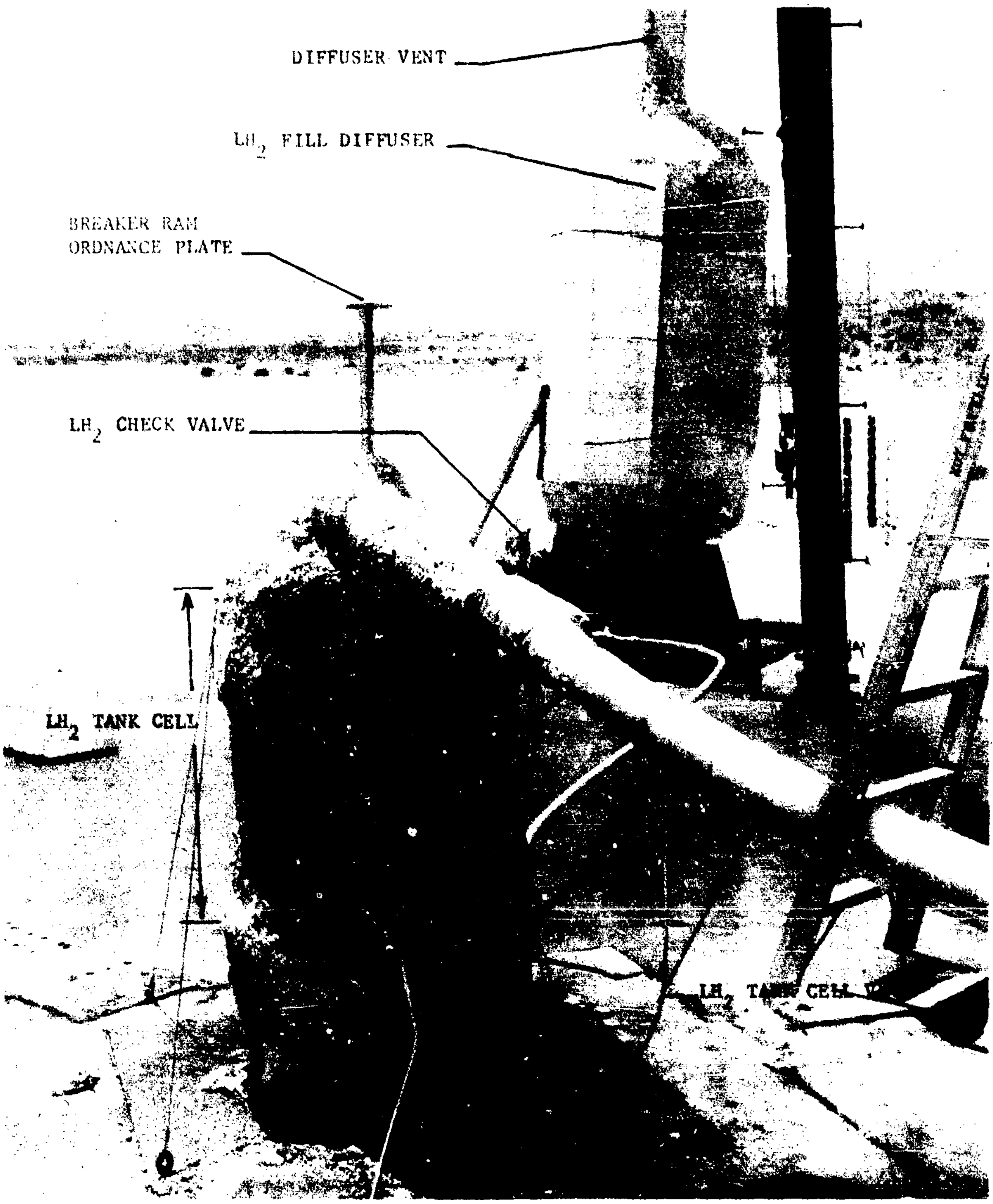


Figure 32 TYPICAL TEST ARTICLE USED FOR 200 LB LO_2/LH_2 CONFINEMENT-BY-THE-MISSILE TEST CONDITION

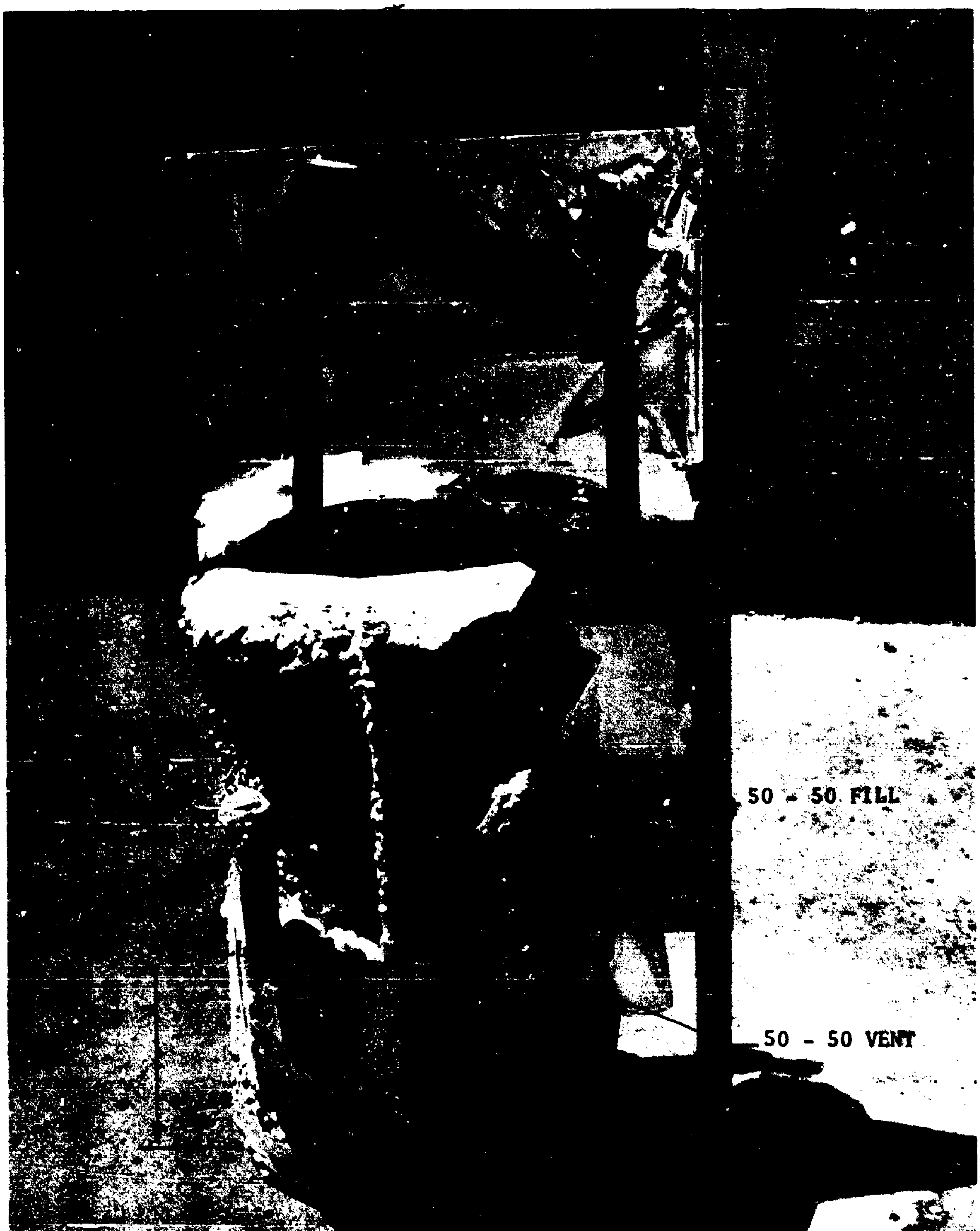


Figure 33 TYPICAL CONFIGURATION USED FOR 200 LB N_2O_4/50% UDMH - 50% N_2H_4 HIGH DROP TEST ARTICLE

REFERENCES

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"BIG MOMMA"

Maj. Mauro Maresca, USAF
Headquarters, U. S. Air Force (AFRST)
Washington, D. C.

A summary of recent Air Force test entitled "BIG MOMMA" was given by Maj. Mauro Maresca, Hq USAF. Full details of this test are available in an official Air Force report. This report is classified SECRET and is distributed through Hq USAF (AFRSTC), Washington, D. C. on a need-to-know basis.

DETONATION CHARACTERISTICS OF LARGE SOLID ROCKET MOTORS

by

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ABSTRACT

The Air Force Rocket Propulsion Laboratory, Edwards, California, is conducting a Solid Propellant Hazards Study Program, Project SOPHY, to analyze the potential explosive hazards of handling, transporting, testing, and launching of large solid-propellant systems. In the initial effort under Project SOPHY, the Aerojet-General Corporation is conducting a combined experimental-theoretical study to answer some questions concerning one aspect of the overall hazards problem, namely the hazard created by the detonation of a large motor containing a Class II solid-composite propellant.

Existing detonation theories are not directly applicable to the analysis of the detonability of conventional solid propellant motor grains, since they consider the propagation of a steady-state detonation in a solid cylindrical charge only, while solid rocket motor grains are normally in the form of cylinders with various shapes of internal perforations. To assess the detonation hazards of real motors, the approach taken in Project SOPHY has been to first determine the minimum diameter (i. e., the critical diameter) of a solid cylindrical grain that will sustain detonation, and then by means of a previously developed Aerojet theory of critical geometry, to relate the critical diameter of the solid cylindrical grain to the critical or minimum size of a given grain shape that will sustain detonation. The critical geometry theory also considers the effect of the size, location, and intensity of the initiating shock stimulus on the initiation of detonation in a supercritical grain.

Parts I and II summarize the results obtained to date on the critical diameter and critical geometry studies, respectively.

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PART I CRITICAL DIAMETER STUDIES

SOPHY I PROGRAM

INTRODUCTION

The objective of the SOPHY I critical diameter program was to develop a mathematical model to predict the critical diameter of a typical Class II propellant. For purposes of this study, the propellant consisted of ammonium perchlorate (AP) oxidizer, aluminum, and an oxygen-lean binder of the polybutadiene-acrylic acid-acrylonitrile (PBAN) type.

Since information available at the inception of the SOPHY studies suggested that the critical diameter of Class II solid-composite propellants might be so large as to economically preclude its direct measurement by full-scale tests, a method was required by which the critical diameter could be predicted from the results of small-scale experiments.

The approach adopted by Aerojet was to determine the critical diameters of composite propellant samples containing various percentages of a high explosive (RDX) adulterant. The experimentally determined curve for critical diameter versus adulterant content was used to guide the concurrent development of the theoretical detonation model to predict the critical diameter of unadulterated Class II propellant.

TEST PLAN

The basic test plan consisted of the determination of the critical diameters of AP-PBAN-Al composite propellant formulations in which decreasing levels of RDX adulterant replaced equal weights of AP. The results of the first group of tests (with propellant samples having the highest RDX content and smallest diameter), together with the concurrently developing theoretical model, were used to select the adulterant level that would bring the critical diameter within the diameter range of the next group of samples. This process was then repeated for each test group. In the absence of a proven theoretical model to guide the early tests, existing data on the effect of RDX addition on the critical diameter of an AP composite propellant was used to select an RDX level of 16 wt % for the first test group. The original test plan with the anticipated RDX levels for each group is shown in Table I.

Because of difficulties in estimating the percentage of RDX needed to cause the critical diameter of the adulterated propellant to fall within the range of test diameters chosen for each test group, it was necessary to cast and test several sample groups in addition to those shown in Table I.

TEST PROCEDURE

The critical diameter tests were conducted with solid cylindrical propellant samples having a length/diameter ratio of 4/1. Detonation was initiated by conical high-explosive boosters (cast TNT) with a height/base ratio of 3/1. The basic test setup consisted of the propellant sample, placed vertically upon a steel witness

plate, with the booster resting on top of the propellant charge. The velocity of the detonation wave induced in the propellant by the booster was monitored by two rows of pin probes placed along opposite sides of the charge, and by high-speed streak photography. The test setup is indicated in Figure 1. For propellant charges of 100 pounds or less (nominally 8 inches in diameter) the tests were conducted at the Aerojet Chino Hills Ordnance Laboratory. All larger tests were conducted at the 1-36D Solid Hazards Test Facility of the Air Force Rocket Propulsion Laboratory. Documentary and high-speed (Fastax) film coverage was provided on all tests conducted at the AFRPL.

TABLE I. CRITICAL DIAMETER TEST PLAN

Test Group	Sample Diameter	Number of Samples	Anticipated RDX Level
1	1-1/4 - 2 in.	32	16 wt %
2	2-4 in.	16	12 - 16 wt %
3	6-9 in.	8	10 - 14 wt %
4	11-14 in.	8	8 - 12 wt %
5	18-27 in.	8	6 - 10 wt %
6	48 in.	4	2 - 8 wt %

EXPERIMENTAL RESULTS

The rasteroscilloscope records of the probe data and the streak camera records from each test were converted to distance-time information and then transformed to average velocity data. The criterion for sustainment of detonation was the stabilizing of the velocity of the detonation wave at a reasonably constant value as it traveled down the charge. Although minor fluctuations of the successive data points were usually observed in a sustained detonation, there was no difficulty in distinguishing this behavior from the fading detonation wave in a subcritical sample. In all tests where satisfactory probe and/or streak-camera records were obtained, their indications were confirmed by the witness-plate results. That is, the sustained detonations punched sharp-edged, full-diameter holes in the plates (with severe break-up in the large tests) while the subcritical samples caused only gross bending of the plates.

The SOPHY I critical diameter test results are summarized in Figure 2.

THEORETICAL PROGRAM

As in a previously developed detonation model for porous propellant (Reference 1) the present model describing the nonideal detonation behavior of RDX-adulterated propellant considers that the energy-release process for propagating detonation is oxidizer decomposition by a grain-burning mechanism, and that the grain-burning process is initiated by uniformly distributed hot spots in a time that is short compared with the grain-burning time.

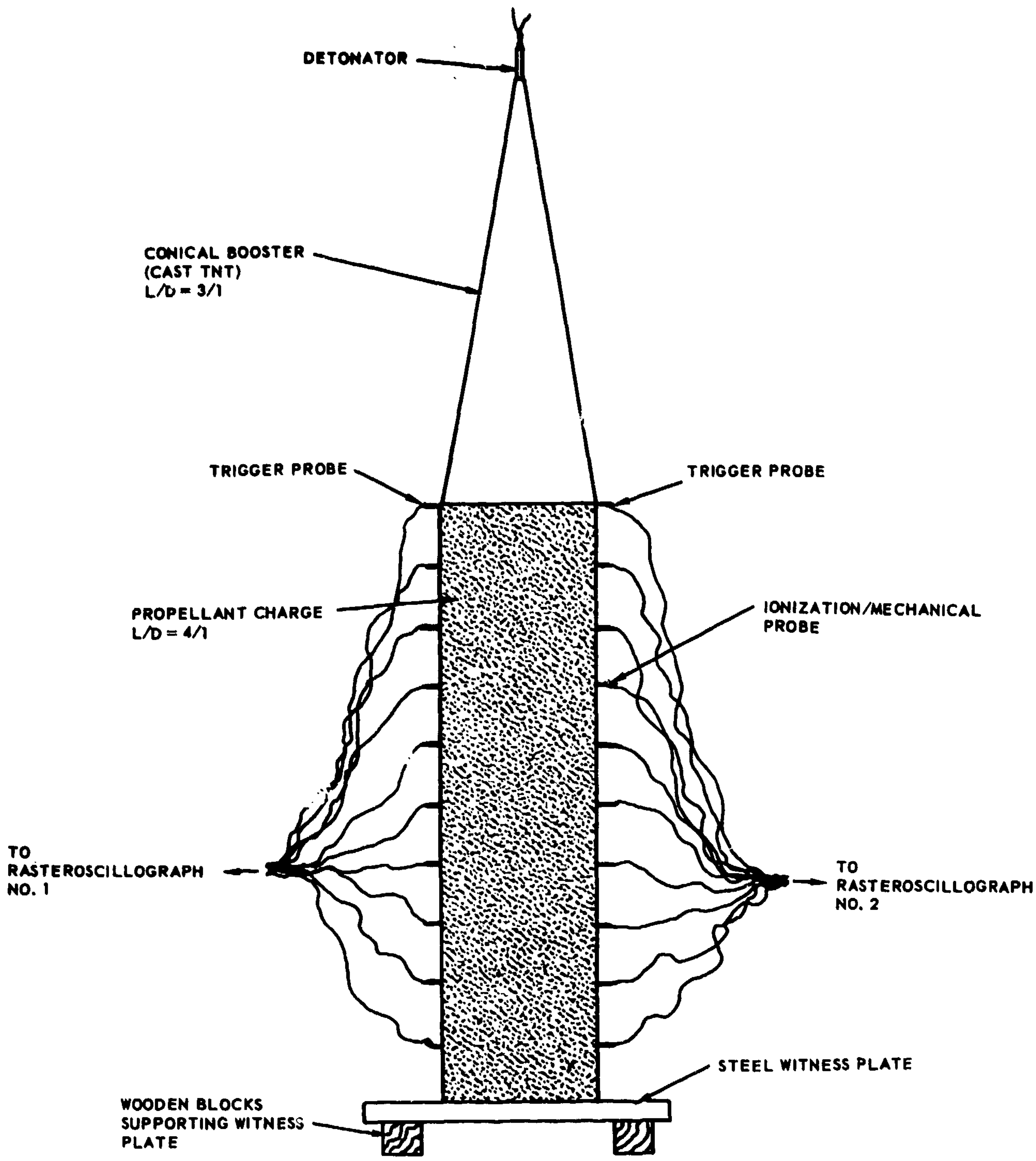

Figure 1. Typical Critical Diameter Test Setup.

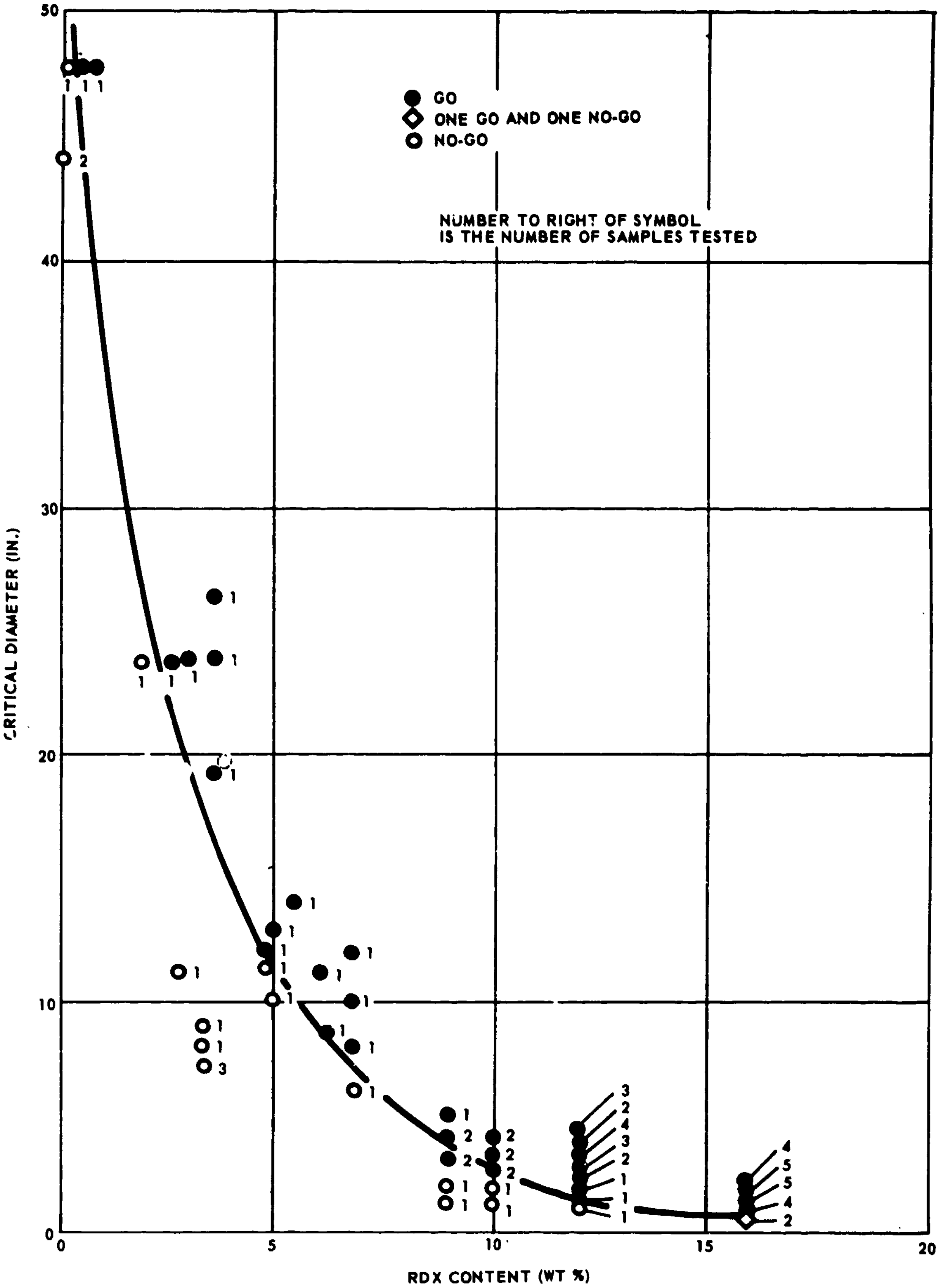

Figure 2. Summary of SOPHY I Critical Diameter Test Results.

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In the present case, the hot spots are provided by the detonating RDX particles. The detonation reaction time is given by

$$t = \frac{R_e}{B} \tag{1}$$

where R_e, the effective grain radius, is one-half the distance between hot-spot initiation sites (detonating RDX particles) and B is the Arrhenius-type rate expression for the linear pyrolysis kinetics of AP (References 1 and 2).

The effective grain radius can be related, from geometric considerations and a knowledge of the propellant composition, to the RDX weight fraction f, and average RDX particle diameter d_{RDX}. Equation 1 then becomes

$$t = \frac{R_e}{B} = \frac{\frac{d_{RDX}}{2}\left[\left(\frac{G}{f}\right)^{1/3} - 1\right]}{B} \tag{2}$$

where G is a constant determined by the propellant composition and the type of assumed geometrical lattice of RDX particles.

By combining Equation 2 with the following expression derived from the Jones theory of nonideal detonation (Reference 3), which relates the detonation velocity D of a charge of diameter d to the ideal (maximum) detonation velocity D_i for a charge of inifinite diameter, and to the detonation reaction time t,

$$d = \frac{kDt}{\left[1-(D/D_i)^2\right]^{1/2}} \tag{3}$$

an expression relating the effect of RDX weight fraction and particle size on the nonideal detonation behavior of RDX-adulterated propellant is obtained. At the critical condition

$$d_c = \frac{kD_c}{} \frac{\left(\frac{d_{RDX}}{2}\right)\left[\left(\frac{G}{f}\right)^{1/3} - 1\right]}{B_c\left[1-(D_c/D_i)^2\right]^{1/2}} \tag{4}$$

If, as a first approximation, it is assumed that D_i and D_c (and therefore B_c, which is a function of D_c) are independent of RDX concentration in the range of RDX contents of interest, then Equation 4 reduces to the form

$$d_c = k_1\left(\frac{1}{f}\right)^{1/3} - k_2 \tag{5}$$

where k_1 and k_2 are constants. Equation 5 predicts that the critical diameter of RDX-adulterated propellant should vary as the reciprocal of the cube root of the RDX content. In Figure 3 the SOPHY I critical diameter data for $f \leq 0.10$ have been plotted in this manner.

Although there are no straight lines of the form of Equation 5 that pass between the "Go" and "No Go" data for all of the test series, solutions exist for RDX contents above about two weight percent. One such solution is

$$d_c = 15.3\left(\frac{1}{f}\right)^{1/3} -30.9 \tag{6}$$

The fact that the simple model (Equation 5) is not in agreement with the critical diameter data at very low RDX contents is not surprising since the model is based on the assumption that initiation sites are supplied only by the RDX particles. However, other types of potential hot spot sites may also exist in these samples. For example, even good-quality conventionally manufactured propellants may be expected to contain some small but finite concentration of minute voids; many internal flaws have also been found in large AP grains. Also, the interactions of converging shocks (e.g., at AP-aluminum grain boundaries) may result in greatly increased local pressures and temperatures. Equation 5 must therefore be modified to include such additional initiation sites (this had been anticipated early in the theoretical program, while the simple model was still in agreement with experiment). As a first approximation, the additional sites may be considered simply as an additional (constant) weight fraction c of RDX particles. Equation 5 then becomes

$$d_c = k_3\left(\frac{1}{f + c}\right)^{1/3} -k_4 \tag{7}$$

where the constants k_3 and k_4 may not be identical with the corresponding constants of Equation 5. One combination of (k_3, k_4, c) that makes Equation 7 consistent with all critical diameter data for $f \leq 0.10$, as found by a graphical trial and error technique, is

$$d_c = 15.3\left(\frac{1}{f + 0.003}\right)^{1/3} -30.4 \tag{8}$$

The agreement of Equation 8 with the critical diameter data is illustrated in Figure 4.

Equation 8, which is consistent with all critical diameter data for

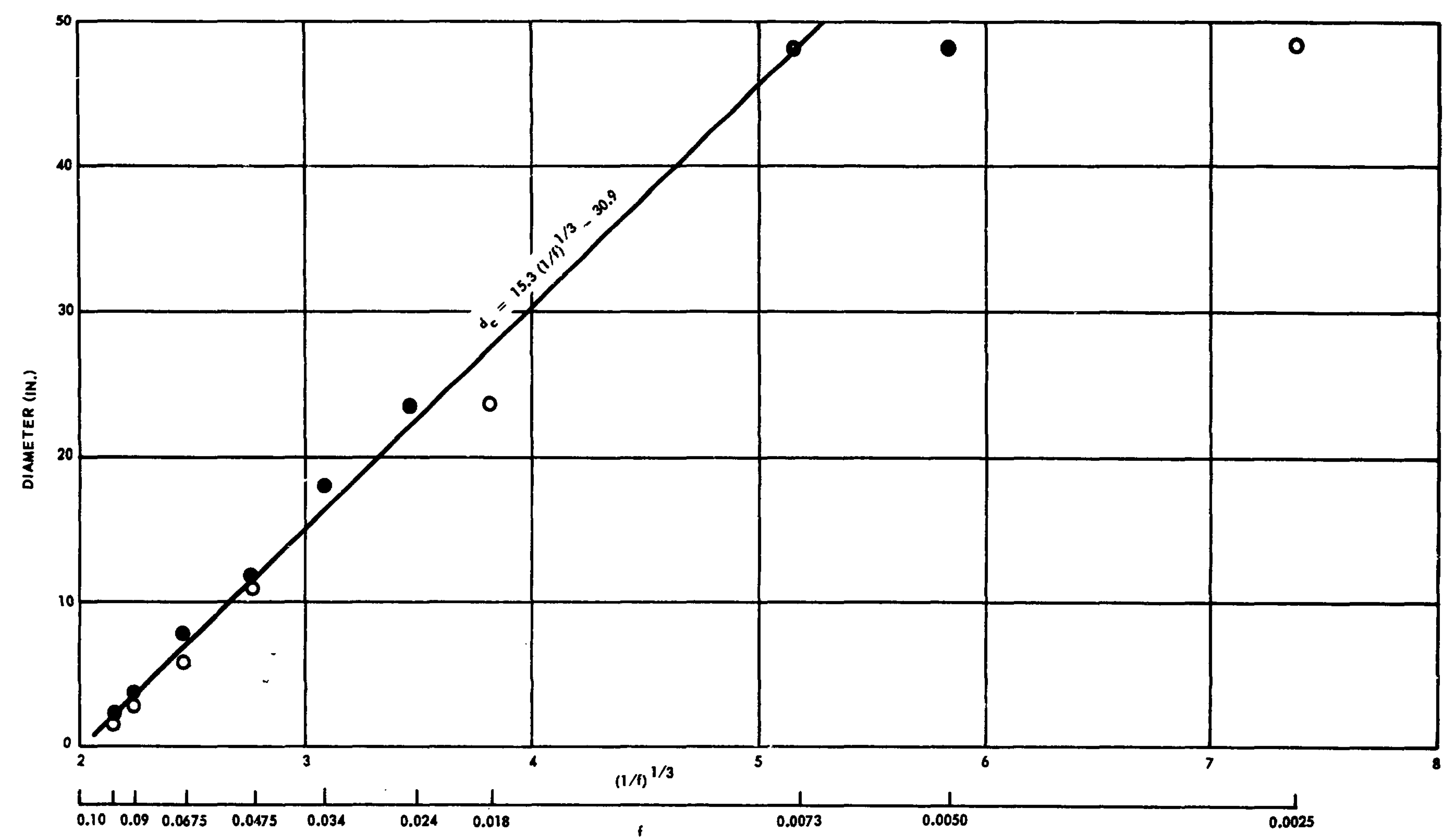


Figure 3. Correlation of SOPHY I Critical Diameter Data Using the Simple Theoretical Model (Equation 5).

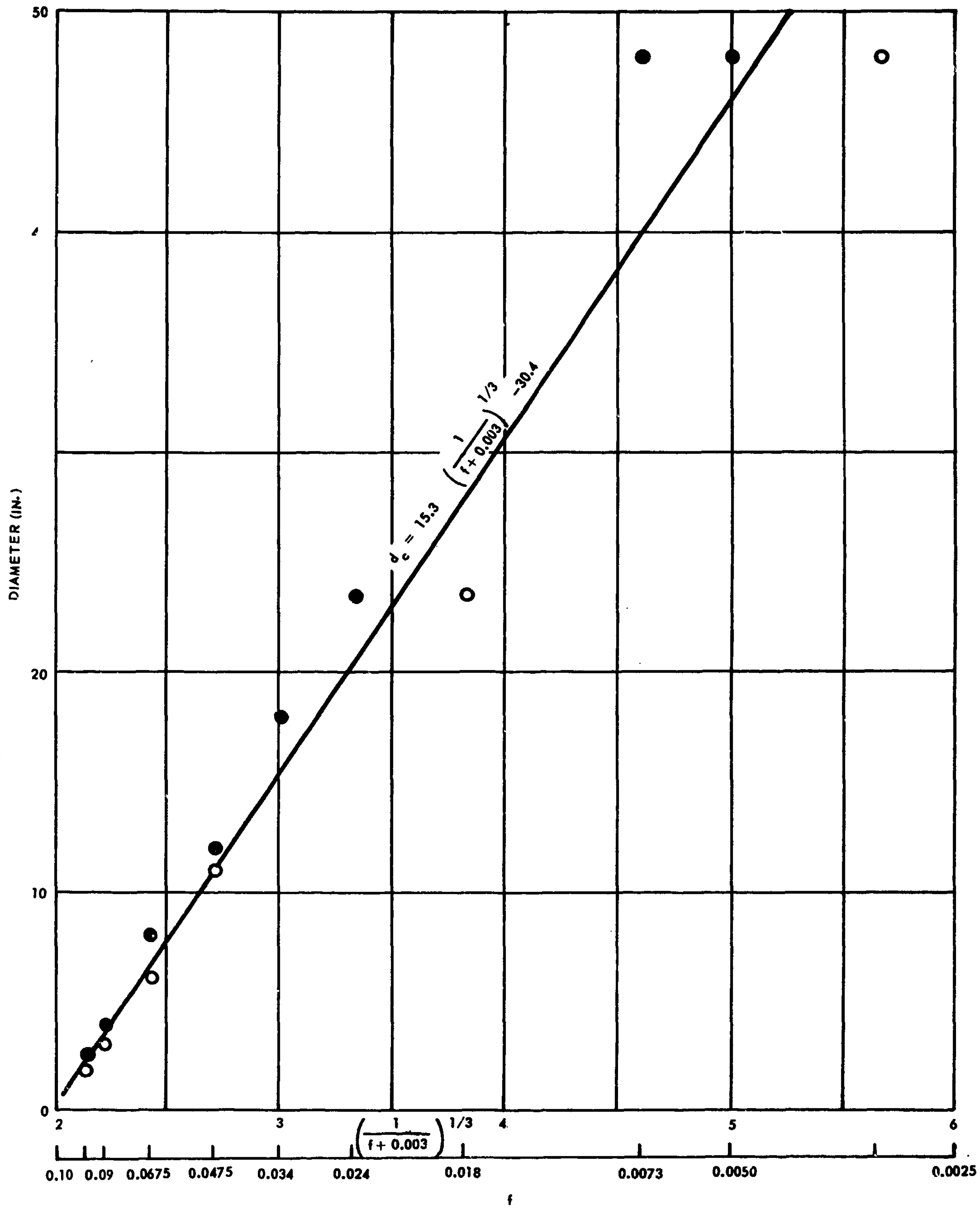


Figure 4. Correlation of SOPHY I Critical Diameter Data Using Refined Theoretical Model (Equation 7).

$f \leq 0.10$, is based on the assumption that D_i, D_c, and B_c in Equation 4 are independent of f in this range of RDX concentrations. When derived expressions for D_i, D_c, and B_c as functions of f (Reference 4) are substituted in Equation 4 (modified by inclusion of the factor c to account for initiation sites other than RDX) the resulting expression is still of this form since the combined functionality

$$g(f) = \frac{D_c}{B_c \left[1-(D_c/D_i)^2\right]^{1/2}} \tag{9}$$

is constant within 1%. The constants k_3 and k_4 may therefore be identified with the parameters of the theoretical model:

$$k_3 = k\left(\frac{d_{RDX}}{2}\right) g(f)\, G^{1/3} \tag{10}$$

and

$$k_4 = k\left(\frac{d_{RDX}}{2}\right) g(f) \tag{11}$$

Where k is th constant in the Jones expression (Equation 3).

Equation 8 may be used to estimate the critical diameter of RDX-adulterated AP-PBAN-Al propellant as a function of f, as well as the critical diameter of the unadulterated AP-PBAN-Al propellant. The results of these calculations are summarized in Figure 5.

DISCUSSION

A comparison of the experimental critical diameter data with the calculated values of critical diameter over the entire range of RDX contents employed in this study lends considerable support to the basic assumptions of the theoretical model as to the important physical and chemical processes involved in propagating detonation in RDX-adultered AP-PBAN-Al propellants.

First, even the simple detonation model, in which the effective AP grain radius (and hence the detonation reaction time and critical diameter) is proportional to $(1/f)^{1/3}$, predicts values of the critical diameter in agreement with the experimental data over a considerable range of RDX contents ($0.10 \geq f \geq 0.018$). This suggests that, for this region of f-values, the assumption that AP grain burning is the predominant energy-release process in the detonation reaction zone is a reasonable one.

Second, the fact that an increasing disparity exists between the calculated critical diameter and the experimental data for $f > 0.10$ is in itself indirect evidence for the grain-burning mechanism. In the detonation model the effective AP grain radius (i.e., half the calculated distance between uniformly distributed RDX particles in a continuous AP matrix) can decrease with increasing RDX content until each RDX particle

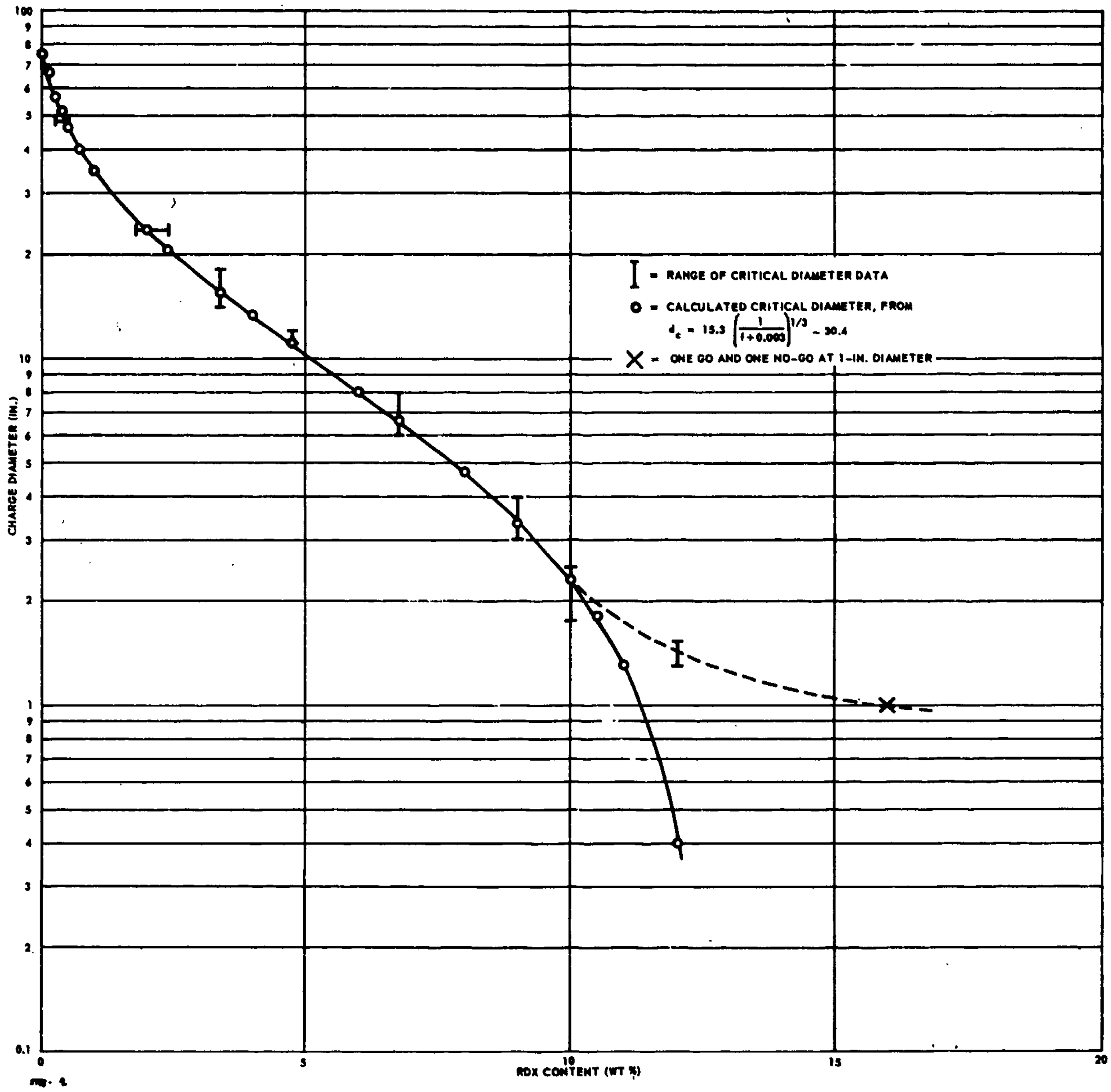


Figure 5. Comparison of Predictions of Theoretical Model with Experimental Critical-Diameter Data.

is in contact with its neighbors (i. e., $R_e = 0$), while in the real situation there will be some RDX level at which R_e will equal the average AP grain radius and any further decrease in R_e with increasing RDX content will be prevented by the AP particles. For the propellants tested in this program this apparently occurs when $f > 0.10$. Grain-burning at higher RDX levels would therefore occur at an essentially constant grain radius, but with an increase in the number of RDX particles surrounding each grain. If the excess RDX particles on the surface of the grains did not affect the grain-burning process, the critical diameter would be expected to remain essentially constant. The fact that the critical diameter actually decreases slowly for $f > 0.10$ (dashed curve on Figure 5) suggests that the energetic decomposition of the RDX particles results in a higher-than-normal linear regression rate for the outer portion of the AP grains. This leads to a somewhat shorter total grain-burning time and hence a somewhat smaller critical diameter than would have resulted had there been no perturbation of the AP grain-burning process by the decomposing RDX particles.

Third, the fact that the simple model (Equation 5) failed at lower values of f (where the inherent initiation sites become a significant fraction of the total number of sites), but could be successfully modified by including a term to account for such additional initiation sites, supports the original assumption that a grain-burning mechanism is involved in propagating detonation in these propellants.

An important implication of the need for an additional parameter in the model to account for inherent initiation sites is that the critical diameter of conventionally-manufactured Class II propellants will be a rather sensitive function of the propellant quality, (i. e., of the number and size-distribution of flaws introduced into the propellant grain either during manufacture or during handling and storage) and of constituents which favor the generation of hot spots by shock interactions.

SOPHY II PROGRAM

The objective of the SOPHY II critical diameter program was to experimentally examine the detonation behavior of unadulterated Class II propellant, using the SOPHY I model to select the appropriate test sample sizes. Because the SOPHY I test configuration (bare single segments) has been significantly changed for the SOPHY II tests, the results of the SOPHY II tests cannot be considered as providing additional data for the SOPHY I model.

SELECTION OF TEST SAMPLE SIZE

As previously noted (Figure 4) there are an unlimited number of solutions of the form of Equation 7 which are compatible with all the ranges of Go No-Go data. As a result there will also be a considerable range of predicted values for the critical diameter of unadulterated propellant. To aid in selecting a sample diameter for the first test with unadulterated propellant, two distinct approaches were used.

The first (nonstatistical) approach consisted of finding those combinations of k3, k4, and c which are consistent with all ranges. In doing this 441,471 unique combinations of these constants were tested using an IBM 7094 computer. Values of k3 ranged from 10.00 to 15.00 in intervals of 0.05, values of k4 from 28.0 to 42.0 in intervals of 0.1, and values of c from 0.0020 to 0.0080 in intervals of 0.0002. Of the 263 total solutions which satisfied all ranges, the following solutions provided the maximum and minimum critical-diameter values for zero-percent RDX, respectively.

$$d_c\ (\max) = 16.1 \left(\frac{1}{f + 0.003}\right)^{1/3} - 32.5 = 79 \text{ inches} \tag{12}$$

and

$$d_c\ (\min) = 18.75 \left(\frac{1}{f + 0.008}\right)^{1/3} - 37.6 = 56 \text{ inches} \tag{13}$$

The midrange between the two extremes is 67.5 in. Table II presents a frequency distribution of the zero-percent RDX critical diameter estimates for all solutions satisfying all ranges. From this table, the median (50%) value of the critical diameter is found to be 64 in.

The second (statistical) approach consisted of fitting best-estimate values of the mean critical diameter, by least squares, to estimated values of k3 and k_4 for selected values of c (this was necessary since k3 and c are not linearly independent in the model). The values of mean critical diameter, at the corresponding RDX percentages, that were used for these fits are:

Critical Diameter (in.)	Weight Fraction RDX
2.125	0.10
2.73*	0.092
3.50	0.090
6.50	0.0675
11.25	0.0475
23.5	0.021
48.0	0.00375

The values of c ranged from 0.0133 to 0.0900 in increments of 0.0033. Table III presents the results of these fits. The fit for c = 0.00533 which was considered best (since it resulted in the smallest standard error of

*Data from critical geometry program

Table II. Frequency Distribution of Zero-Percent RDX Critical-Diameter Estimates for Solutions Satisfying all Ranges

Critical Diameter (in.)	Frequency Tally	Number	Cumulative Number	Cumulative Percent
56	~~IIII~~	5	5	1.9
57	~~IIII~~ ~~IIII~~ II	12	17	6.5
58	~~IIII~~ ~~IIII~~ ~~IIII~~ I	16	33	12.5
59	~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~	20	53	20.2
60	~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ III	23	76	28.9
61	~~IIII~~ ~~IIII~~ ~~IIII~~ II	17	93	35.4
62	~~IIII~~ ~~IIII~~ I	11	104	39.5
63	~~IIII~~ ~~IIII~~ ~~IIII~~	15	119	45.2
64	~~IIII~~ ~~IIII~~ ~~IIII~~ III	18	137	52.1
65	~~IIII~~ ~~IIII~~ IIII	14	151	57.4
66	~~IIII~~ ~~IIII~~ ~~IIII~~ I	16	167	63.5
67	~~IIII~~ ~~IIII~~ II	12	179	68.1
68	~~IIII~~ ~~IIII~~ II	12	191	72.6
69	~~IIII~~ ~~IIII~~	10	201	76.4
70	~~IIII~~ ~~IIII~~ III	13	214	81.4
71	~~IIII~~ IIII	9	223	84.8
72	~~IIII~~ ~~IIII~~	10	233	88.6
73	IIII IIII	9	242	92.0
74	~~IIII~~ I	6	248	94.3
75	IIII	4	252	95.8
76	IIII	4	256	97.3
77	IIII	4	260	98.9
78	I	1	261	99.2
79	II	2	263	100.0

Table III. Results of Least-Squares Fits to Critical-Diameter Data

c	k_3	k_4	s_e*	Critical Diameter at 0% RDX (in.)
0.00133	12.580	24.001	1.55	90.4
0.00167	13.015	25.015	1.39	84.7
0.002	13.427	25.971	1.24	80.6
0.00233	13.831	26.901	1.090	77.4
0.00267	14.239	27.834	0.96	74.8
0.003	14.627	28.718	0.82	72.7
0.00333	15.009	29.583	0.70	70.9
0.00367	15.396	30.454	0.59	69.4
0.004	15.766	31.283	0.48	68.0
0.00433	16.131	32.096	0.39	66.9
0.00467	16.502	32.918	0.30	65.8
0.005	16.857	33.701	0.24	64.9
0.00533	17.208	34.472	0.224	64.0
0.00567	17.566	35.253	0.24	63.3
0.006	17.909	36.00	0.30	62.6
0.00633	18.249	36.736	0.37	61.9
0.00667	18.595	37.483	0.44	61.3
0.007	17.929	38.199	0.52	60.8
0.00733	19.259	38.905	0.60	60.2
0.00767	19.597	39.624	0.68	59.7
0.008	19.922	40.314	0.75	59.3
0.00833	20.245	40.995	0.82	58.9
0.00867	20.575	41.689	0.90	58.5
0.009	20.893	42.356	0.96	58.1

*s_e = standard error of estimate $\sqrt{\frac{(y-\hat{y})^2}{n-1}}$

estimate; 0.224 in.) gives a critical diameter of 64 in. for zero-percent RDX.

To obtain an estimate of the variance of critical diameter at zero-percent RDX, it is necessary to have estimates of the variances of k_3, k_4, and c. The variance of d_c can then be estimated, using the standard propagation-of-error technique:

$$V(d_c) = \left(\frac{\partial d_c}{\partial k_3}\right)^2 V(k_3) + \left(\frac{\partial d_c}{\partial k_4}\right)^2 V(k_4) + \left(\frac{\partial d_c}{\partial c}\right)^2 V(c) \quad (14)$$

where V (x) is the variance of x, and the partial derivatives are evaluated at their expected values. The variances of k_3 and k_4 are, by standard least-squares regression formulas, equal to 0.0088 and 0.077 respectively.

The variance in c cannot be obtained from the least-squares fit. To estimate its variance it was assumed that the 6 σ spread for c was 0.005. (This value was deduced from the results of the nonstatistical approach, which revealed that, for all the solutions satisfying all ranges, the value of c varied from 0.003 to 0.008). Assuming c to be distributed normally and the 6 σ range to be 0.005, the variance of c is calculated to be 6.94×10^{-7}. Using these values as the estimated variances of k_3, k_4, and c, the variance in d_c at zero-percent RDX becomes 26.85 in. squared. The estimated standard deviation at zero-percent RDX is then 5.18 in. This produced 3 σ limits of from 48.5 to 79.5 in. about the mean value of 64 in.

On the basis of these analyses, a diameter of 72 in. was selected for the first critical-diameter test with unadulterated propellant. Although a diameter of this size does not ensure a 100% probability of detonation, the probability is sufficiently high to justify its selection. The nonstatistical approach (Table II) indicates a probability of 0.89 that the critical diameter of unadulterated propellant will be below 72 in., in that 88.6% or 233 of the 263 solutions gave solutions for the critical diameter less than or equal to 72 in. An even higher probability is indicated by the statistical approach. Assuming that critical diameters are normally distributed at zero-percent RDX with a mean of 64.0 in. and a standard deviation of 5.18 in., a 72-in. diameter would be 1.54 standardized normal units above the mean value. Thus, the probability of 72 in. equalling or exceeding the critical diameter is approximately 0.94, Giving equal weight to both analyses, the probability of a detonation at 72 in. is greater than 90%.

EXPERIMENTAL PROGRAM

TEST DESIGN

The SOPHY II tests were conducted in essentially the same basic configuration as the SOPHY I tests (Figure 1). However, certain problems created by the large size of the test articles necessitated the following major modifications in the detailed design of the charges.

First, because of limitations in casting, X-raying, and field handling equipment, it was necessary to construct the large samples by stacking a number of short cylindrical segments. Second, stress analyses indicated that the hydrostatic pressure created at the base of the large charges by the weight of propellant plus TNT booster would cause considerable deformation of the propellant, so that it was necessary to test the samples in a confining metal jacket.

The TNT boosters for the present tests were similar in design to those used in SOPHY I in that they consisted of a series of stacked cylindrical segments of decreasing diameter to approximate a cone having a height equal to three base diameters. However, in the present case, the boosters were removed from their casting molds before testing to eliminate a large source of fragment material from the test article.

72-Inch Critical Diameter Test

The test setup is shown schematically in Figure 6. The levelled test pad consisted of a square concrete ring measuring 10 ft on a side. The sides of the ring were 1 ft wide at the top, 21 in. wide at the bottom, and buried 4 ft deep in the soil. The soil inside the ring was removed to a depth of approximately 8 in. to provide the customary air gap beneath that portion of the steel witness plate under the charge. The witness plate was a slab of mild steel, 6 in. thick by 10 ft square, weighing approximately 12 tons. The propellant acceptor charge was constructed at the test site from five 6-ft-diameter by 4.8-ft-high segments of ANB-3226 propellant. Each segment contained more than 7 tons of propellant. The total propellant weight was approximately 37 tons. The segments were shipped in their molds from Aerojet's Solid Rocket Operations Plant at Sacramento. At the test site, each mold was removed and an 0.080-in.-thick aluminum cylindrical restraining fixture was fastened around the bare propellant. The propellant segments were lifted into their final positions by a vacuum chuck assembly. The TNT booster, consisting of stacked segments each measuring 3 ft thick, had an estimated weight of 9 tons. The detonator was placed in a cone of C-4 explosive on top of the booster. The completed test article was about 42 ft high and weighed approximately 50 tons.

Ionization probes of two designs were used with separate rasteroscillograph systems to provide detonation-velocity data. The probes were placed along the length of the propellant sample in two rows, located 90° apart on the charge surface. Holes in the restraint girdles provided access to the propellant surface at the probe sites. Blast instrumentation was provided by Kistler Type 601H and 701A side-on gauges, Type 601H face-on gauges, and a Kistler amplifier. The output from the system was recorded directly on FM tape, using Ampex FR1200 (120 ips) and Ampex ES100 (60 ips) recorders.

The probe-rasteroscillograph records indicated a sustained detonation over the lower 2-1/2 diameters of the charge, with an average detonation velocity of 3.2 mm/μsec. The observed velocity is clearly supersonic and

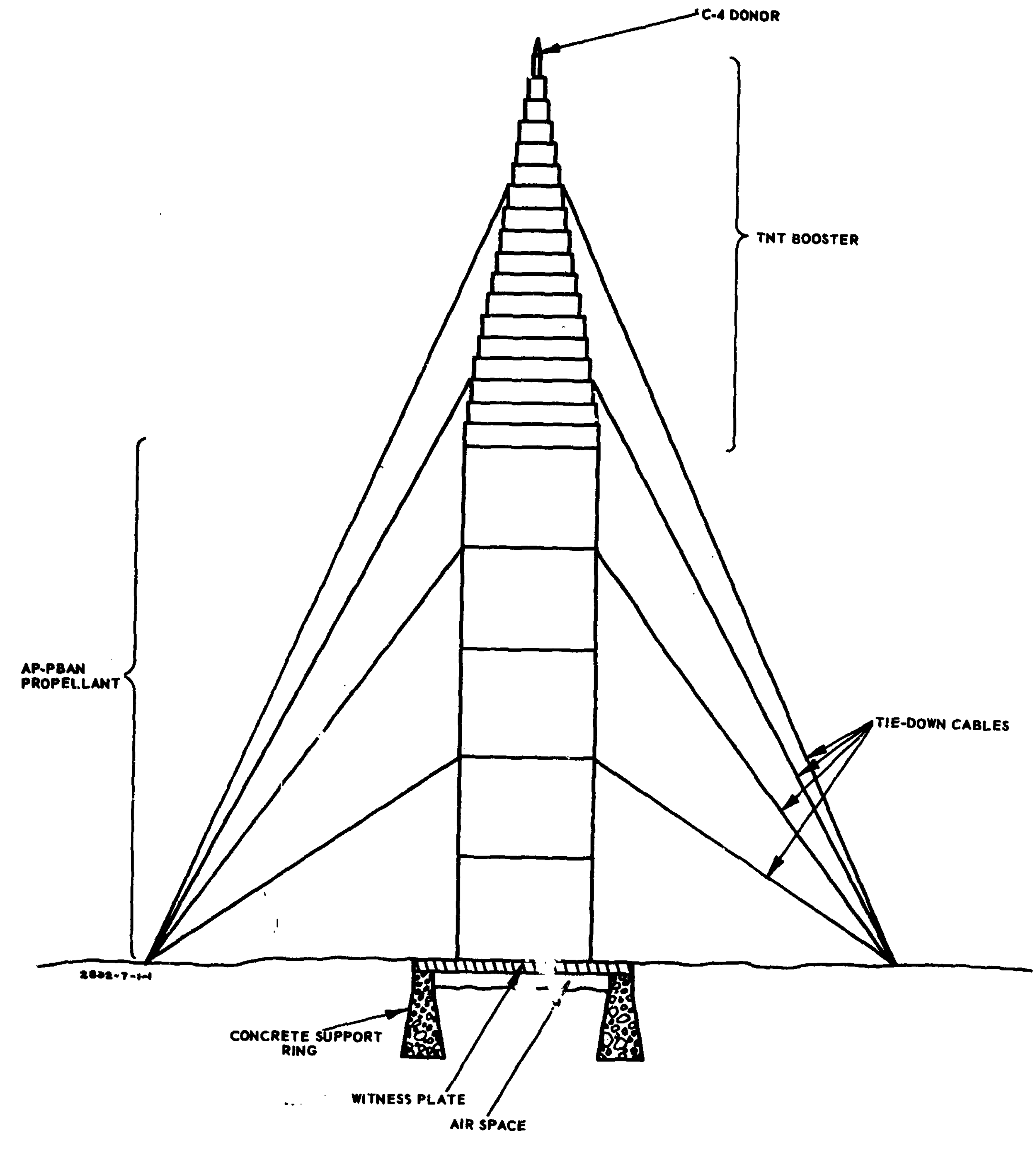


Figure 6. 72-in. Critical Diameter Test.

steady state. From these data it is concluded that the sample sustained detonation. Figure 7 shows the plotted values of detonation velocity versus distance down the charge.

Additional information as to the nature of the reaction can be obtained by comparing the witness plate with the witness plates from the 48-in. diameter SOPHY I critical diameter tests. In both of the 48-in. "Go" tests, with propellant containing 0.73 and 0.50% RDX, the witness plates were punched and strong evidence of metal flow was observed at those portions of the plates beneath the charge periphery. In the 48-in. "No Go" test, with propellant containing 0.25% RDX, the witness plate was dished but not broken. The fact that the witness plate in the 72-in. test with unadulterated propellant was extensively broken up suggests that a detonation had propagated throughout the charge. However, recovered fragments did not show the metal flow characteristic of previous "Go's". This apparently anomolous result may be attributed to the fact that the (calculated) pressure associated with the low detonation velocity of 3.2 mm/μsec did not transmit a sufficiently high pressure to permanently deform or punch the witness plate. The crater produced by the test measured 32 ft in diameter and 10 ft deep (to the backfill level).

Visual observation of the test and subsequent examination of the photographic records indicated that no burning propellant was expelled. This evidence, together with the fact that burning propellant had been observed in all previous "No Go's" in SOPHY I tests, also suggests that the event was a "Go".

60-Inch Critical Diameter Test

Selection of a 60-in.-size for the final test was based on the fact that the 72-in.-size was a "Go" and that a 48-in.-dia sample of adulterated propellant containing 0.25 wt % RDX had not sustained detonation in a SOPHY I test (and hence a 48-in.-dia sample of unadulterated propellant should also be subcritical). The 60-in.-size therefore bisects the unknown region between 48 and 72 in.

The basic design and the method of assembly of the 60-in. test charge were similar to that of the 72-in. charge. The propellant charge was erected on a 6-in.-thick by 10-ft-square steel witness plate. It consisted of four 5-ft-diameter by 5-ft-high segments of ANB-3226 propellant. An 0.080-in.-thick aluminum restraining skin was placed around each segment. The total propellant weight was approximately 43,200 lb. The segmented conical cast TNT booster weighed approximately 10,700 lb.

Detonation velocity data was obtained from a streak-camera record and from rasteroscillograph records from three types of pin probes (ionization, ionization/mechanical, and mechanical) placed along the length of the propellant sample. Blast instrumentation was the same as that which was used in the 72-in. test.

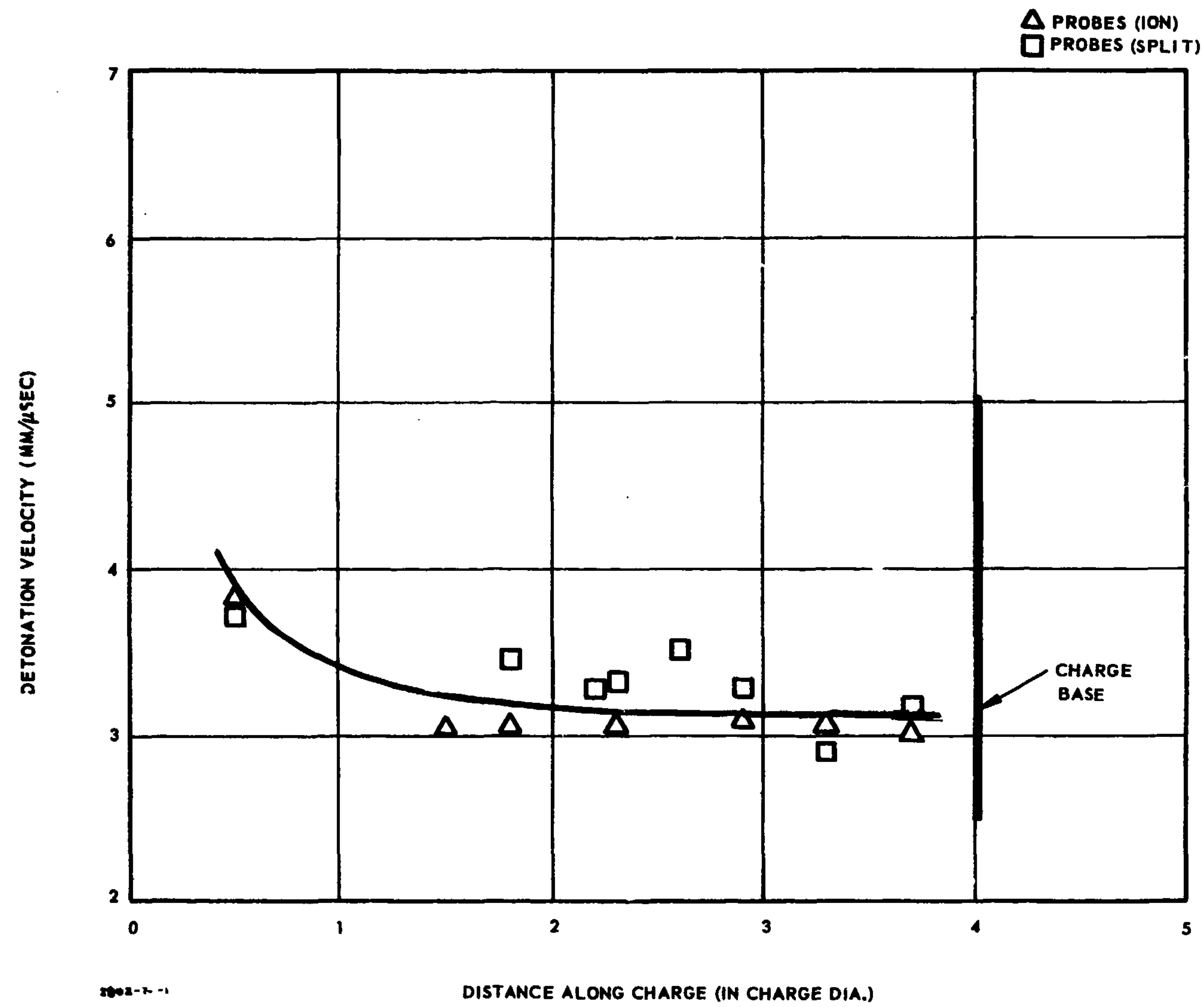


Figure 7. Detonation Velocity vs Distance Along Charge, 72-in. -Diameter ANB-3226 Propellant Charge (0 Wt % RDX).

Statistical analysis of the detonation velocity vs distance data from the streak camera record and the probe records indicated that the detonation wave was slowly decaying when it reached the bottom of the charge (i. e., the velocity-distance curve had a slightly negative slope which differed significantly from zero). The witness plate was slightly dished but intact. The earth in the vicinity of ground zero was depressed slightly but no crater was formed. Considerable burning propellant was expelled from the charge.

Although analysis of the data from this test is still in progress, it was concluded from the above evidence that the event was a "No-Go".

Blast Data

Preliminary overpressure data obtained from the Kistler blast-pressure gauges in the 72-in. and 60-in. tests are listed in Table IV. They are included here to provide a qualitative indication of the explosive behavior of the propellant. No particular significance should be attached to these data until they have been verified by a more detailed examination of the blast records. Also included in Table IV are overpressures and TNT equivalences calculated by solution of the Rankine-Hugoniot equations using time-of-arrival data obtained at the gauge stations. Since this method is generally applicable to the pressure range of 5 to 90 psi, calculated values are shown only within this range.

SUMMARY

The results of the SOPHY II large critical diameter tests confirm the predictions of the SOPHY I detonation model, i. e., the typical aluminized AP composite propellant (ANB-3226) tested in this program will sustain steady-state detonation in diameters on the order of 5 to 6 ft. This behavior is expected to be typical of other Class II AP composite propellants of similar composition, with the major influence on the magnitude of the critical diameter being the concentration of inherent hot-spot initiation sites (e. g., cast-in voids, flaws, and constituents which facilitate formation of local regions of high temperature by shock interactions).

It must be emphasized that although solid cylindrical samples of composite propellants are capable of sustaining detonation, this fact has no direct bearing on the detonation hazards of large solid boosters containing hollow-cored grains of such propellants. A hazards analysis requires first that the relation between (1) the detonability of a solid cylindrical charge and a hollow-cored charge of given core geometry, and (2) the strength (and location) of the shock stimulus required to initiate the detonation be determined. This information will be supplied by the critical geometry studies of Project SOPHY. If the propellant grain in the solid booster is found to be detonable in its particular size and geometry, the degree of hazard can then be assessed by determining the probability of supplying the proper stimulus from the booster's operational environment (e. g., by catastrophic failure of an adjacent stage).

Table IV. Observed and Calculated Side-on Overpressure and TNT Equivalences in the 72-in. and the 60-in. Critical Diameter Tests.

(IMPORTANT: The data presented in this table are preliminary. Their values are subject to change pending further reduction and analysis.)

Radial Distance from Charge (ft)	Radial Direction (o'clock)	Peak Side-on Overpressure† Measured (psi) 72-in. Test	Measured (psi) 60-in. Test	Calculated (psi) 72-in. Test	Calculated (psi) 60-in. Test	TNT Equivalence From Measured Overpressure (%) 72-in. Test	From Measured Overpressure (%) 60-in. Test	From Calculated Overpressure (%) 72-in. Test	From Calculated Overpressure (%) 60-in. Test
140	2	**	125	-	-	**	199	-	-
	6	**	**	-	-	**	**	-	-
	10	**	126	-	-	**	201	-	-
250	2	54.0	31.0	-	-	223	177	-	-
	6	50.3	25.4	-	-	208	129	-	-
	10	*	24.2	-	-	*	120	-	-
375	2	**	**	20.2	10.7	**	**	193	128
	6	**	**	19.9	10.4	**	**	188	121
	10	**	**	19.6	10.4	**	**	184	121
500	2	10.1	6.12	-	-	155	124	-	-
	6	*	6.90	-	-	*	157	-	-
	10	**	6.68	-	-	**	147	-	-
600	2	**	**	6.81	4.11	**	**	136	103
	6	**	**	6.71	3.98	**	**	131	95
	10	**	**	6.35	4.24	**	**	128	110
700	2	5.82	3.91	-	-	177	160	-	-
	6	*	3.74	-	-	*	145	-	-
	10	5.51	3.79	-	-	151	150	-	-
1000	2	2.98	2.09	-	-	132	127	-	-
	6	2.90	2.05	-	-	126	121	-	-
	10	2.95	2.22	-	-	130	149	-	-
1500	2	1.45	**	-	-	92	**	-	-
	6	1.72	1.09	-	-	145	91	-	-
	10	1.57	**	-	-	115	**	-	-

† Measured overpressures are derived from Kistler transducer measurements. The calculated overpressures are calculated at midpoint distances between Kistler transducer stations from which time-of-arrival data are available. The calculations are performed using an equation derived from the Rankine-Hugoniot equations:

$$p = \frac{2\gamma}{\gamma + 1} P_o \left(\frac{U^2}{c_o^2} - 1 \right)$$

where p = peak overpressure on the shock front
γ = ratio of specific heats for air
P_o = test-site atmsopheric pressure
U = velccity of shock front
c_o = sound velocity at test site

*No data, because of gauge failure.

**No side-on overpressure gauge placed at this location.

PART II CRITICAL GEOMETRY STUDIES

OBJECTIVES

The objective of the second part of this program was to develop a reliable theory of critical geometry for predicting the conditions under which detonation could take place in non-right-solid-cylindrical systems. Specifically, this task was divided into two phases:

1. Determine the critical dimensions for the sustainment of detonation of various (nonperforated and perforated) shapes.

2. Determine an initiation criterion and demonstrate the applicability of this criterion in predicting the detonation of nonperforated and perforated cylinders using various-size cylindrical donors at various locations.

These objectives were studied with an AP-PBAN-Al composite propellant, (containing 9.2 wt % RDX) with a critical diameter of approximately 3 in.

THEORY

The current theory of critical geometry is presented in detail elsewhere (Reference 4). However, a brief summary of the main features of the theory is useful in understanding the objectives and results of this program.

The critical geometry theory determines the detonability of a given system formulation by answering the two questions:

1. Is the given configuration capable of supporting detonation?

2. If the configuration is capable of supporting detonation, are sufficient (shock) forces available to initiate detonation?

The first question is answered by analyzing the gains and losses of energy in a detonation, and by geometrical reasoning developing a "critical" condition for any configuration, expressed as a simple algebraic equation. This equation relates the critical dimensions of any shape to the critical diameter of a right-solid cylinder, and determines if it is capable of detonation. Applying this equation to various shapes (nonperforated and perforated) gives the results shown in Figures 8 and 9.

The second question is partly answered by considering the parameter (shock pressure) most important in causing shock-initiated detonation, assuming that the minimum shock pressure required to initiate detonation is independent of shape but varies with size, and then postulating an "initiation criterion" (a property of

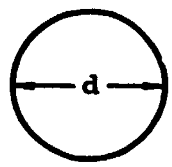
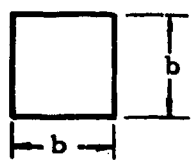
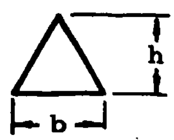
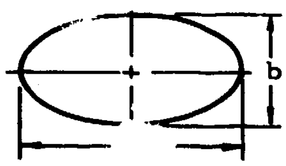
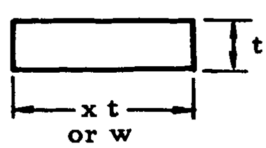
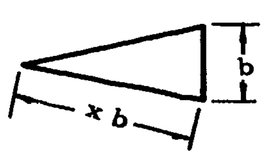
SHAPE AND CHARACTERIZING DIMENSIONS		CRITICAL VALUE OF CHARACTERIZING DIMENSIONS
CIRCLE		$d_c = d_c$
SQUARE		$b_c = d_c$
EQUILATERAL TRIANGLE		$b_c = (\sqrt{3})\, d_c$ or $h_c = (\frac{3}{2})\, d_c$
ELLIPSE WHERE: $x > 1$		$b_c = \left[\dfrac{\int_0^{\pi/2} \sqrt{1 - \frac{x^2 - 1}{x^2} \sin^2 \phi}\; d\phi}{\pi} \right]$ $b_{c_\infty} = \lim_{x \to \infty} b_c = \dfrac{d_c}{\pi}$
RECTANGLE WHERE: $x > 1$		$t_c = \left(\dfrac{x+1}{2x}\right) d_c$ $t_{c_\infty} = \lim_{x \to \infty} t_c = \dfrac{d_c}{2}$ or if w is fixed $t_c = \dfrac{w d_c}{2w - d_c}$
ISOSCELES TRIANGLE WHERE: $x > 1$		$b_c = \sqrt{\dfrac{2x+1}{2x-1}}\; d_c$ $b_{c_\infty} = \lim_{x \to \infty} b_c = d_c$

Figure 8. Critical Dimensions of Various Shapes - Nonperforated Grains.

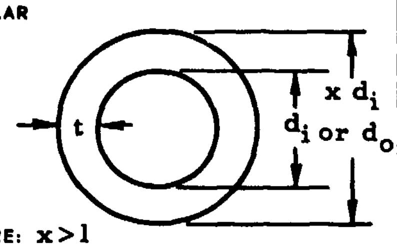
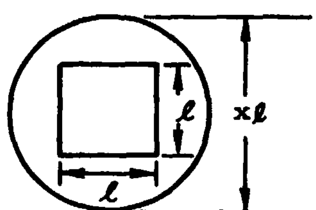
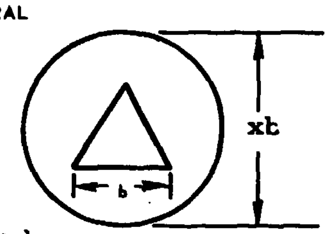
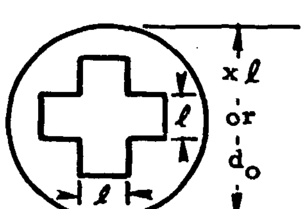
SHAPE AND CHARACTERIZING DIMENSIONS	CRITICAL VALUE OF CHARACTERIZING DIMENSIONS
CIRCULAR CORE  WHERE: $x > 1$	$d_{i_c} = \left(\frac{1}{x - 1}\right) d_c$ or $t_c = \frac{d_c}{2}$ or if d_i is fixed $d_{o_c} = d_i + d_c$
SQUARF CORE  WHERE: $x > 1$	$\ell_c = \left(\frac{\pi x + 4}{\pi x^2 - 4}\right) d_c$
EQUILATERAL TRIANGLE CORE  WHERE: $x > 1$	$b_c = \left(\frac{\pi x + 3}{\pi x^2 - \sqrt{3}}\right) d_c$
CROSS CORE  WHERE: $x > 1$	$\ell_c = \left(\frac{\pi x + 12}{\pi x^2 - 20}\right) d_c$ or if ℓ is fixed $d_{o_c} = \frac{d_c}{2}\left[1 + \sqrt{1 + \frac{16\ell}{\pi d_c}\left(5\frac{\ell}{d_c} + 3\right)}\right]$

Figure 9. Critical Dimensions of Various Shapes - Perforated Grains.

the given material) expressed in terms of shock pressure. The second question is then fully answered by considering this "initiation criterion" and determining if the shock input from a given stimulus meets the requirement of the criterion. If so, initiation of detonation takes place.

EXPERIMENTAL STUDIES

During this program, experiments were carried out to evaluate the theory of critical geometry. In conducting the program three batches of propellant were cast and 81 critical geometry tests performed. Another 19 tests were made for calibration purposes.

Because many instrumented tests were required, a specific test site at Aerojet's Chino Hills Ordnance Laboratory was selected and secured for this program. This site has facilities for using high-speed framing and/or streak cameras and rasteroscillograph techniques.

SUSTAINMENT OF DETONATION

During this program 38 sustainment of detonation tests were performed. In each test, the determination of a steady detonation ("Go") or a transient detonation ("No Go") was based on a careful reduction, examination, and evaluation of the reaction velocity-distance data generated by the streak camera and/or rasteroscillograph system, as well as the witness-plate test result. The range of critical dimensions was determined from the test dimensions below which there were no more "Go's" and the test dimensions above which there were no more "No Go's".

Nonperforated Shapes

The shapes considered among nonperforated shapes were the circle and the equilateral triangle. The objective of each subtask was to determine the critical dimensions of the particular shape. The prediction of the current theory of critical geometry for these shapes is shown in Figure 8.

Critical Diameter (Circle) Tests

Nineteen critical diameter tests were performed using samples from all three batches of propellant. The test setup is illustrated in Figure 10, while an analysis of the results is shown in Figure 11. Although a high degree of certainty was placed on most of the determinations in Figure 11, when evidence for the particular judgement was subject to any doubt, an open (rather than filled-in) box was used.

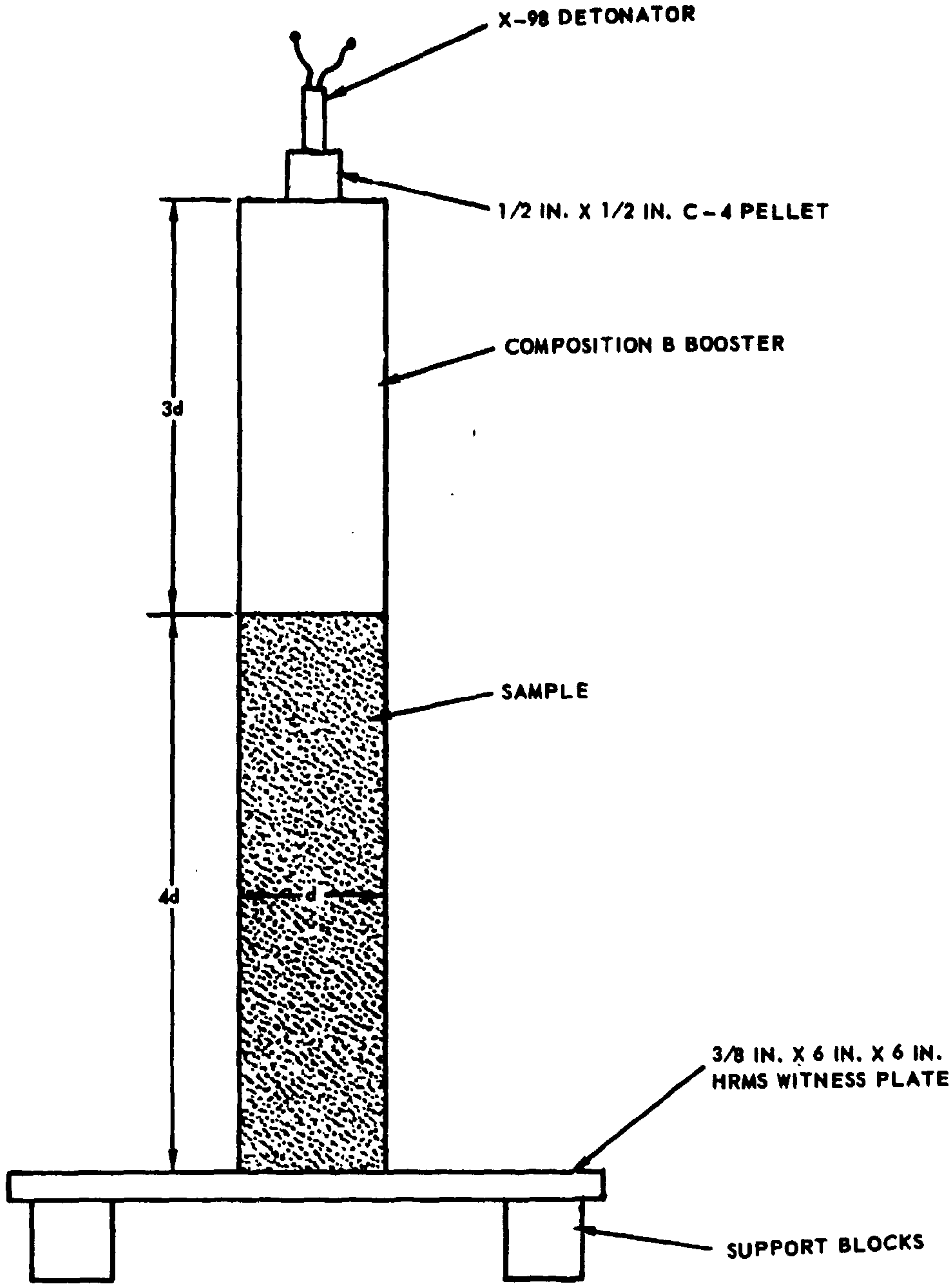


Figure 10. Test Setup - Critical Diameter Tests.

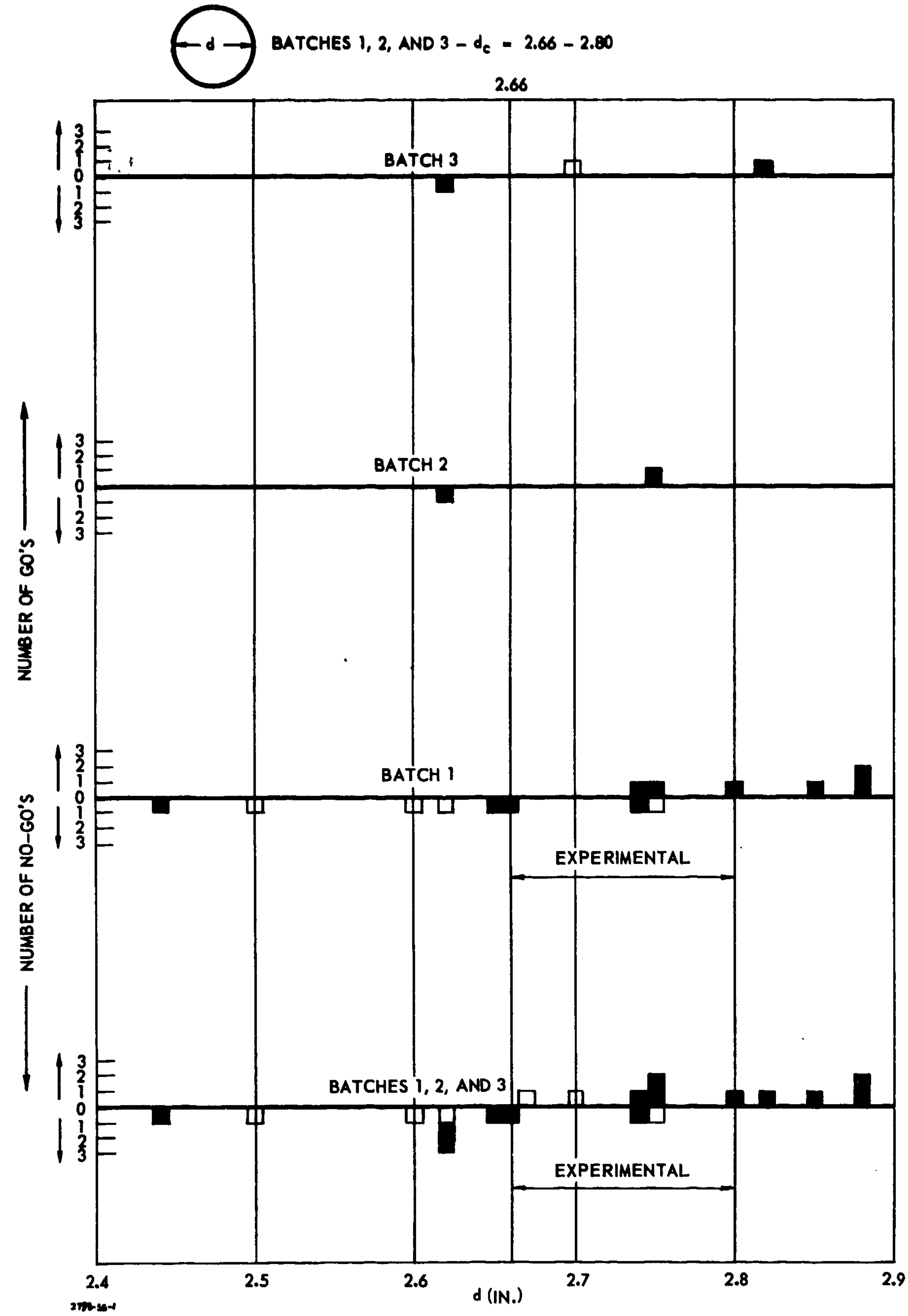


Figure 11. Analysis of Critical Diameter Tests.

From Figure 11 it was tentatively concluded that the critical diameter d_c of Batch 1 of this material is between 2.66 and 2.80 in. It may be noted that the individual results for Batches 2 and 3 are consistent with each other and with those for Batch 1. For this reason the critical diameter of these batches was assumed to be the same as for Batch 1.

Critical Equilateral Triangle Tests

Six critical equilateral triangle tests using samples from the second batch were made. The test setup is similar to that shown in Figure 10 and the analysis of the results is shown in Figure 12. The result is somewhat below the value predicted by current theory.

Perforated Shapes

The perforated shapes considered were the circular-core cylinder and the cross-core cylinder. The objective of each subtask was to find the critical outside diameter of the shape for a fixed inside dimension. The prediction of the current theory for circular and cross-core cylinders is shown in Figure 9.

With the central cavity left empty, a jet was produced in the central cavity of the hollow core charges that punched the witness plate, which, at first, made it difficult to distinguish a "Go" from a "No Go" in a particular test. However, from a study of central cavity jetting by Sultanoff (Reference 5) and a careful examination of the streak camera and rasteroscillograph records, it was possible to formulate a proposed mechanism for this phenomenon and on this basis make a determination of which charges did or did not detonate. This is discussed more fully in the Appendix.

Critical Circular-Core Cylinder Tests

Four critical circular-core cylinder tests using samples from the third batch were performed. The test setup for the first two tests was similar to that shown in Figure 10 except a circular-core booster and a line wave generator were used. The test setup for the remaining two tests was again similar to that shown in Figure 10 except that a 1-in. thick Plexiglas attenuator was used between the booster and sample. The analysis of the results is shown in Figure 13. Because of limited data, no specific conclusions were made but the indication was that the critical circular-core outside diameter d_{o_c} of PBAN-RDX explosive was between 3.54 and 4.02 in.

Critical Cross-Core Cylinder Tests

Five critical cross-core cylinder tests using samples from the third batch were made. The test setup is similar to that shown in Figure 10 except that the 1-in. Plexiglas attenuator was used. The analysis of these results is presented in Figure 14 where it is shown that the critical cross-core outside diameter d_{o_c} is between 3.87 and 4.00 in.

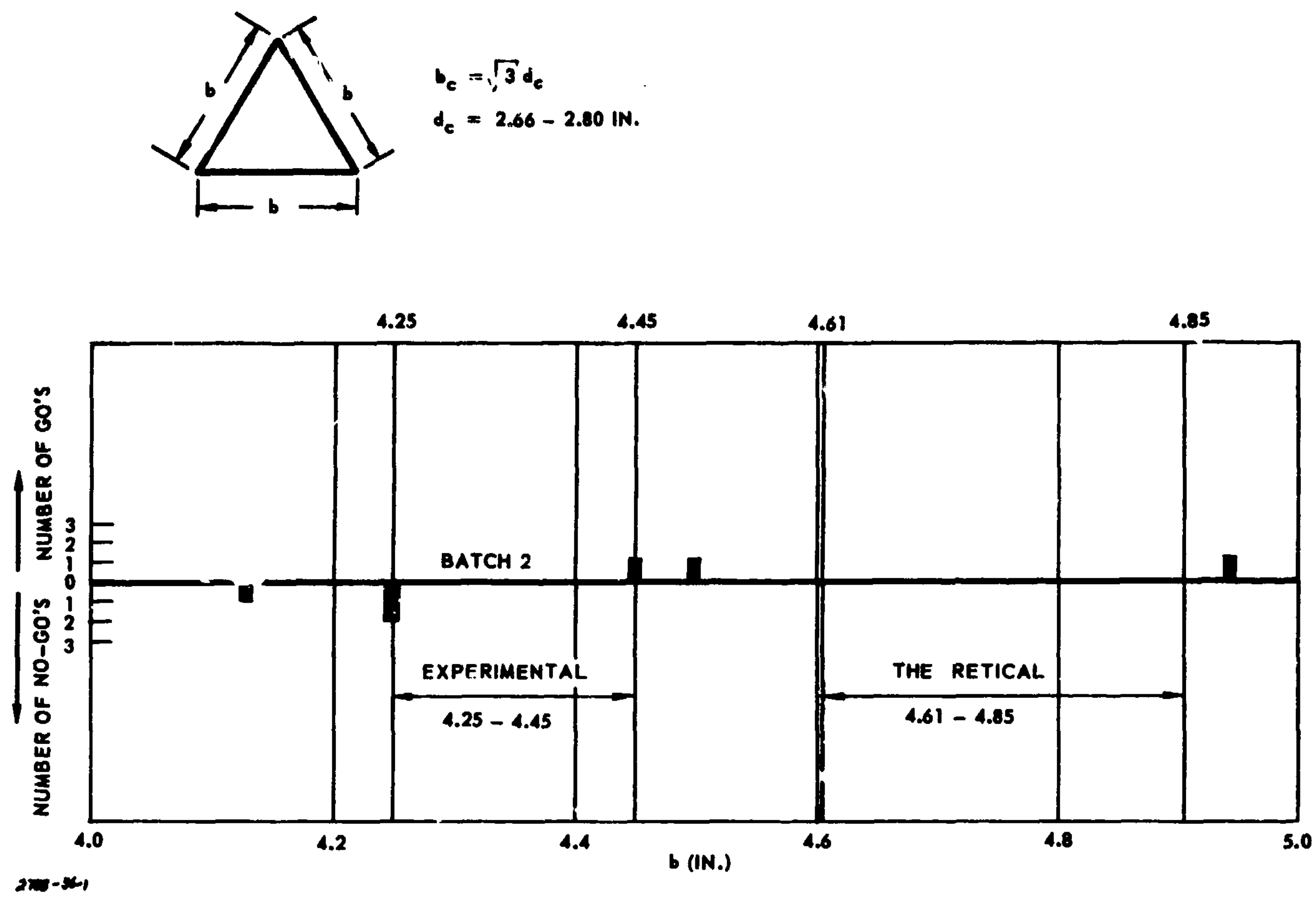


Figure 12. Analysis of Critical Equilateral Triangle Tests.

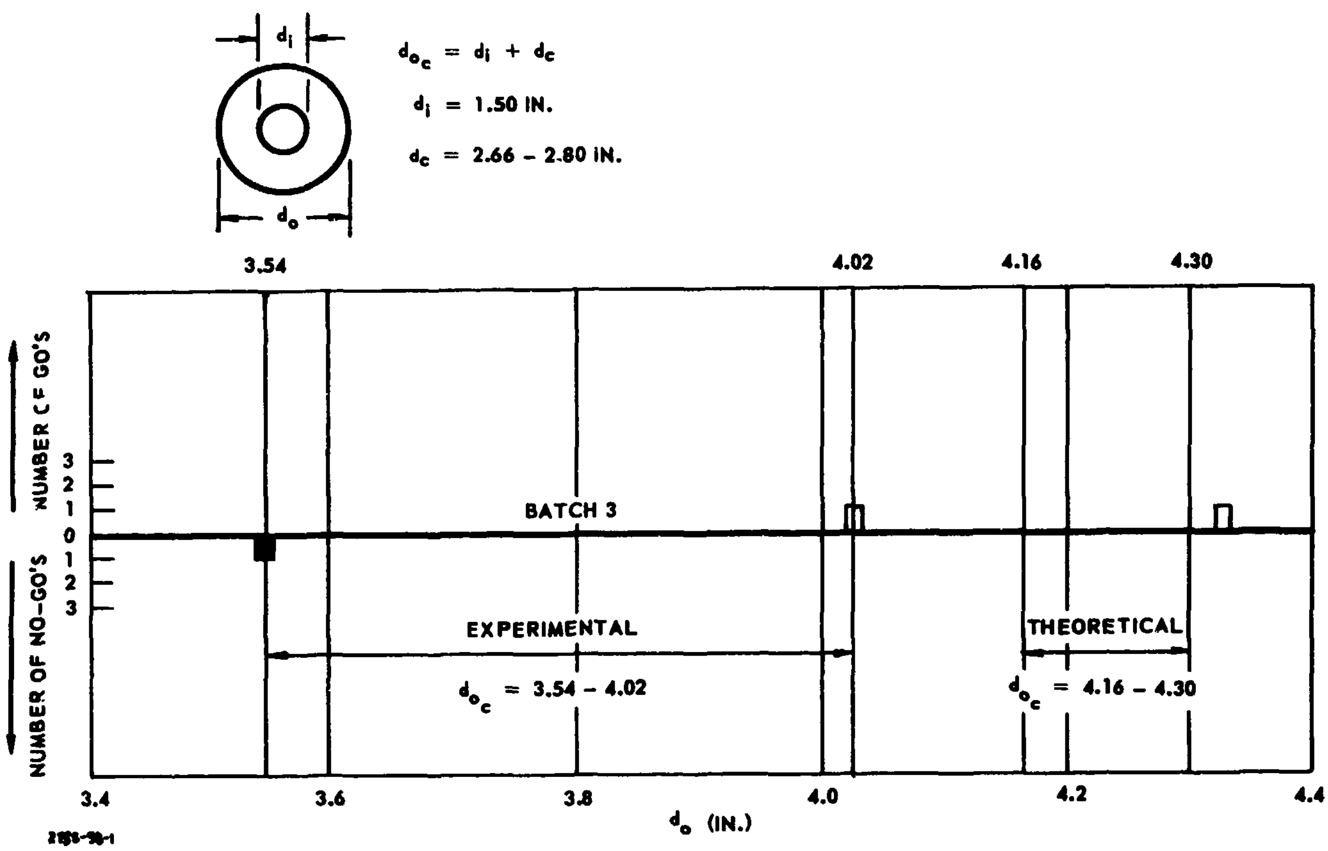
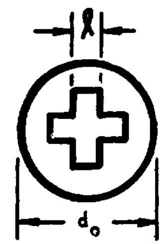


Figure 13. Analysis of Critical Circular-Core Cylinder Tests.



$$d_{o_c} = \frac{d_c}{2}\left[1 + \sqrt{1 + \frac{k\ell}{\pi d_c}\left(S\frac{\ell}{d_c} + 3\right)}\right]$$

$$\ell = 0.475 \text{ IN.}$$

$$d_c = 2.66 - 2.80 \text{ IN.}$$

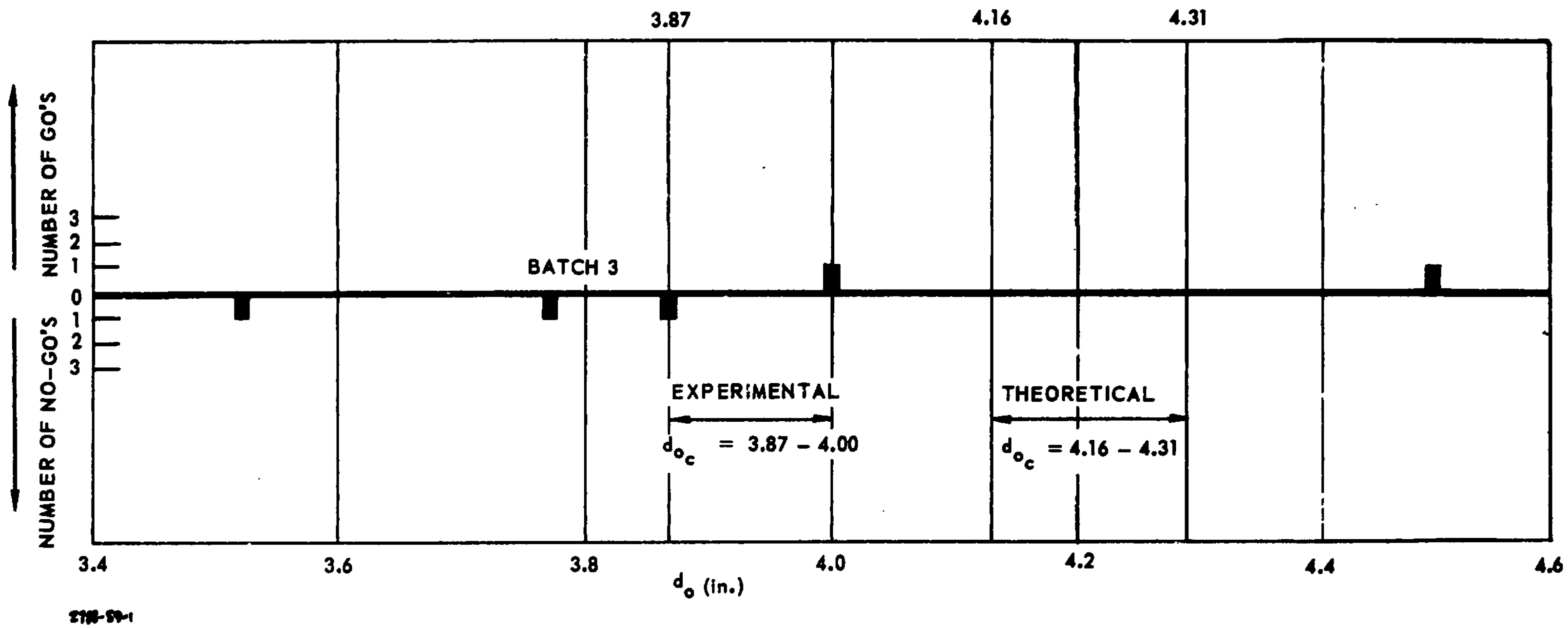


Figure 14. Analysis of Critical Cross-Core Cylinder Tests.

Summary of Sustainment of Detonation Tests

A summary of the results for perforated and nonperforated shapes is presented in Table V. An examination of these results shows that the critical geometry theory is high in predicting the critical dimensions for both solid and perforated shapes. The magnitude of the necessary adjustment in the theory amounts to a range of about 3 to 20%. In an attempt to correlate these results on an equal basis, an equivalent diameter, d'_c, was computed by using the equations in Figures 8 and 9 and solving for the diameter associated with the critical dimension found. The range of these values is shown in Table V. Because the ranges are very similar, these values might be close enough to constitute a basis for correlating data for other shapes. That is, if the equations in Figures 8 and 9 are used to compute the critical dimensions of any shape (perforated and nonperforated), use of d'_c ($\simeq$ 2.4 in.) instead of d_c ($\cong$ 2.7 in.) should give the true value within about 5%. Furthermore, since the total range for each shape is equal to or greater than the corresponding range for the critical diameter, a relatively high degree of confidence may be placed on the supposition that the true critical dimension is in the given range, even though only limited numbers of tests were conducted.

Because of the relatively high quality of the samples, and of the definitiveness of the data obtained with these samples, it may be tentatively concluded that for this material the current critical geometry theory gives an excellent first estimate of the critical geometry of any shape and this estimate may be improved by using a simple adjustment factor, the equivalent diameter.

The critical web thickness of a circular-core cylinder appears to be considerably less than the critical diameter. The range of critical web thickness is from 1.19 to 1.25 in., while the critical diameter range is from 2.66 to 2.80 in. These figures show that the critical web thickness is only from 42 to 47% of the critical diameter thus implying that the critical web thickness of hollow-core propellant grains is probably closer to one-half the critical diameter of the material than to the critical diameter itself.

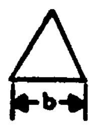
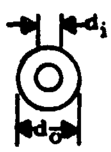
INITIATION OF DETONATION

During this effort, 43 initiation of detonation and 19 associated tests were performed. Again, determination of a steady or transient detonation was made by the streak camera and/or rasteroscillograph reaction velocity-distance data as well as by the witness plate test results.

Sensitivity Measurements

The objective of these tests was to determine an initiation criterion for the AP-PBAN-Al propellant containing 9.20 wt % RDX. This was done using standard card-gap sensitivity tests which were calibrated in terms of shock pressure

Table V. Summary of Critical Geometry Tests

Shape	Batch Number	Range of Critical Dimension: Symbol	Range of Critical Dimension: Theoretical (in.)	Range of Critical Dimension: Experimental (in.)	Equivalent Diameter d_c' (in.)	% Difference in Theoretical and Experimental*
	1, 2, 3	d_c	--	2.66 to 2.80	--	--
	2	b_c	4.61 to 4.85	4.25 to 4.45	2.45 to 2.57	-3.6 to -14.1
 d_i = 1.50 in.	3	d_{oc}	4.16 to 4.30	3.54 to 4.02	2.04 to 2.52	-3.5 to -21.5
 ℓ = 0.475 in.	3	d_{oc}	4.16 to 4.31	3.87 to 4.00	2.38 to 2.51	-4.0 to -11.4

$$*\% \text{ difference} = \frac{\text{Experimental} - \text{Theoretical}}{\text{Experimental}} \times 100$$

knowing the impedance mismatch at the attenuator-sample interface. This was accomplished by determining the initial shock pressure in the attenuator (Plexiglas) for the Composition B booster, measuring the shock pressure attenuation in Plexiglas for various diameter columns, and determining the Hugoniot of the propellant. The criterion was then computed.

Initial Shock Pressure

The initial shock pressure in Plexiglas from a Composition B booster was determined from two tests conducted with a 1-in. diameter by 2-in. long (Composition B) booster resting on a 1/8-in. thick blast shield and a 1-in. long Plexiglas rod. The shock wave produced in the rod (near the interface) was observed with a streak camera. By extrapolating the resulting data to the interface, the value of the initial shock velocity was found to be 7.25 mm/μsec.

Using the previously reported Hugoniot of Plexiglas (Reference 6), the value of the initial shock pressure in Plexiglas was found to be 188 kbar. This value was used in subsequent determinations.

Shock Attenuation

To determine the shock attenuation in Plexiglas, 10 tests were conducted with a test setup similar to that just described except that the blast shield was 1/4 in. thick and column diameters of 3, 3-1/2, 4, 5, and 6 in. (for both the booster and Plexiglas) were used. The Plexiglas acceptors had a length equal to the column diameter. A streak camera followed the shock wave propagation in each test and the resulting data (shock velocity-distance) were converted to shock pressure-distance data again using the Hugoniot of Plexiglas (Reference 6). This data was then correlated by plotting the ratio of the shock pressure to the initial shock pressure against the ratio of distance to column diameter. A universal attenuation curve for Plexiglas cylinders of 3, 3-1/2, 4, 5, and 6 in. in diameter was obtained.

Hugoniot Measurements

To determine the Hugoniot of the propellant, seven tests were conducted. The test setup used is a variation of a well-known technique for measuring the Hugoniot of opaque materials and depends on measuring the shock velocity in the Plexiglas immediately before the shock wave enters the opaque propellant and the shock velocity in the propellant. The resultant data were best-fit to the quadratic expression (as determined by the method of least-squares):

$$P = 33.27\,\mu + 44.45\,\mu^2, \text{ kbar } (\mu \text{ in mm}/\mu\text{sec})$$

This was used in subsequent determinations.

Initiation Criterion

In order to determine the initiation criterion, 32 card-gap sensitivity tests at five diameters were conducted with the standard test setup, using samples from all three batches. Using the value of the initial shock pressure (188 kbar), values of the shock pressure at the end of the column P_p for each test were computed using the universal shock attenuation curve. Knowing the Hugoniot of the propellant, values of P_R (the shock pressure entering the sample) were computed using the Hugoniot "reflection method" (Reference 7). A plot of the shock pressure entering the sample P_R vs charge diameter d is shown in Figure 15. The vertical span drawn between the "Go" and "No Go" results at any diameter represents the region where the shock pressure required to cause detonation P^+ may be found. Accordingly, the best eye-fit curve was drawn through these data. Knowing that detonation cannot be sustained below the critical diameter d_c of the material, a left-hand bound on the curve was drawn at 2.73 in. (the mid-point of the critical diameter range determined previously). This curve is the desired initiation criterion since it divides the pressure-diameter plane into "Go" and "No Go" regions.

Because it is also possible to define the initiation criterion using area of the wave instead of diameter of the test, a criterion alternative to that of Figure 15 was found as follows. Assuming spherical expansion of the detonation wave from the point of initiation in each test, it was possible from the test dimensions and geometry to determine the area of the wave entering the propellant in each case. It was found that this area varied only slightly from test to test at the same diameter and thus an average area A for each diameter was established. The area A_c, associated with critical diameter d_c, was computed by extrapolation of this data. From these computations, the initiation criterion in terms of A was drawn and is shown in Figure 16.

Attenuation Properties

The primary objectives of these tests were to determine in detail how the input shock waves attenuated when axial, end donors of various sizes were placed on nonperforated, supercritical, cylindrical acceptor charges. A secondary objective was to estimate the critical size of the donor required to cause detonation.

The results of five axial, end donor tests using samples from the first and third batches are shown in Table VI. The test setup is shown in Figure 17. In order to follow the progress of the entering shock wave for each test in detail, sets of probes were inserted at depths of 0.5, 1.0, 1.5, and 2.0 in. into the charge. The vertical distance between probes was 1 in. The resultant distance-time data were interpolated to establish the position and size of the wave at any time as well as the vertical velocity of propagation at the different insertion depths at any time. From this information it was desired to determine the wave diameter and area as well as shock pressure, as it attenuated.

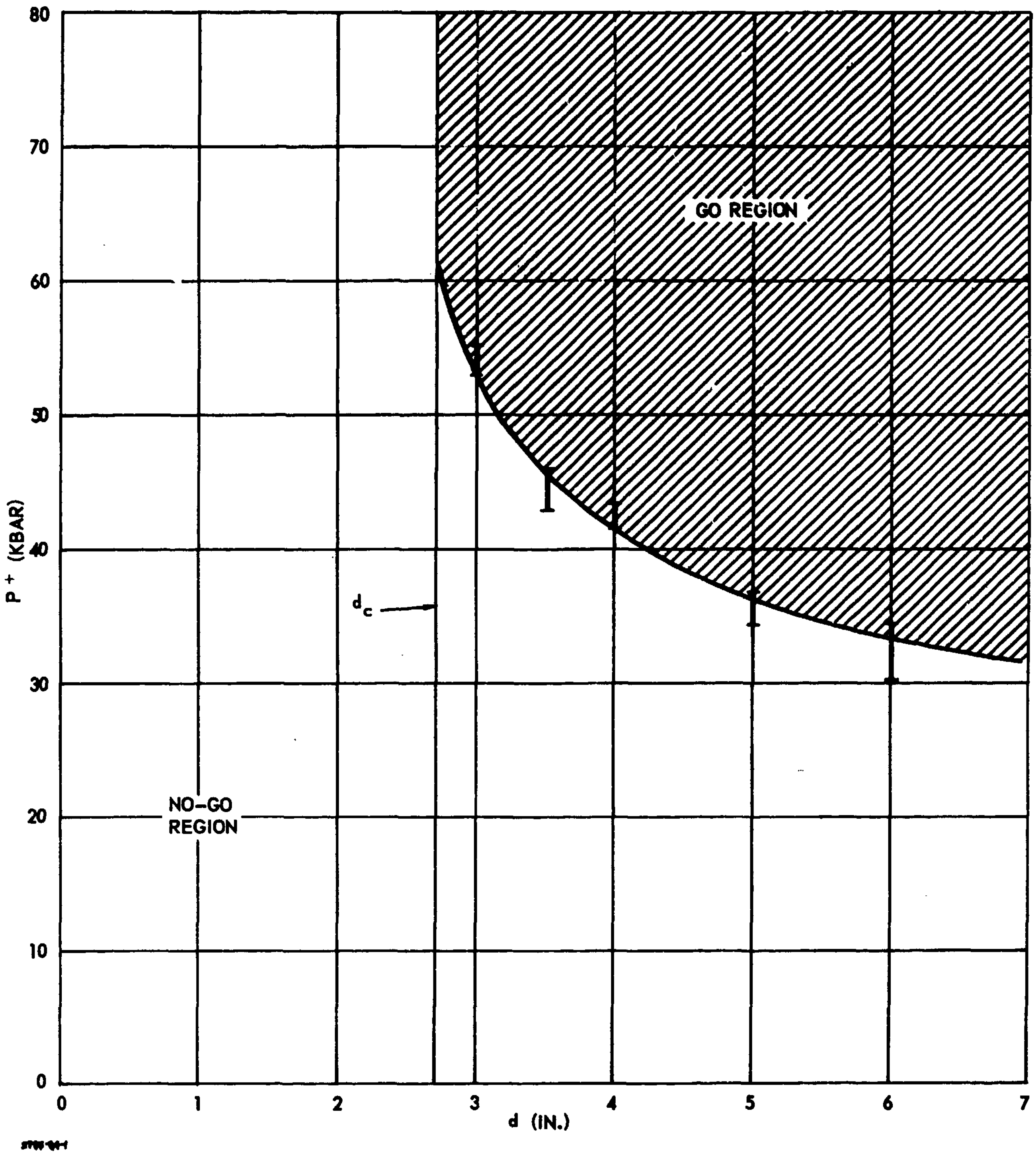


Figure 15. Initiation Criterion P^+ vs d.

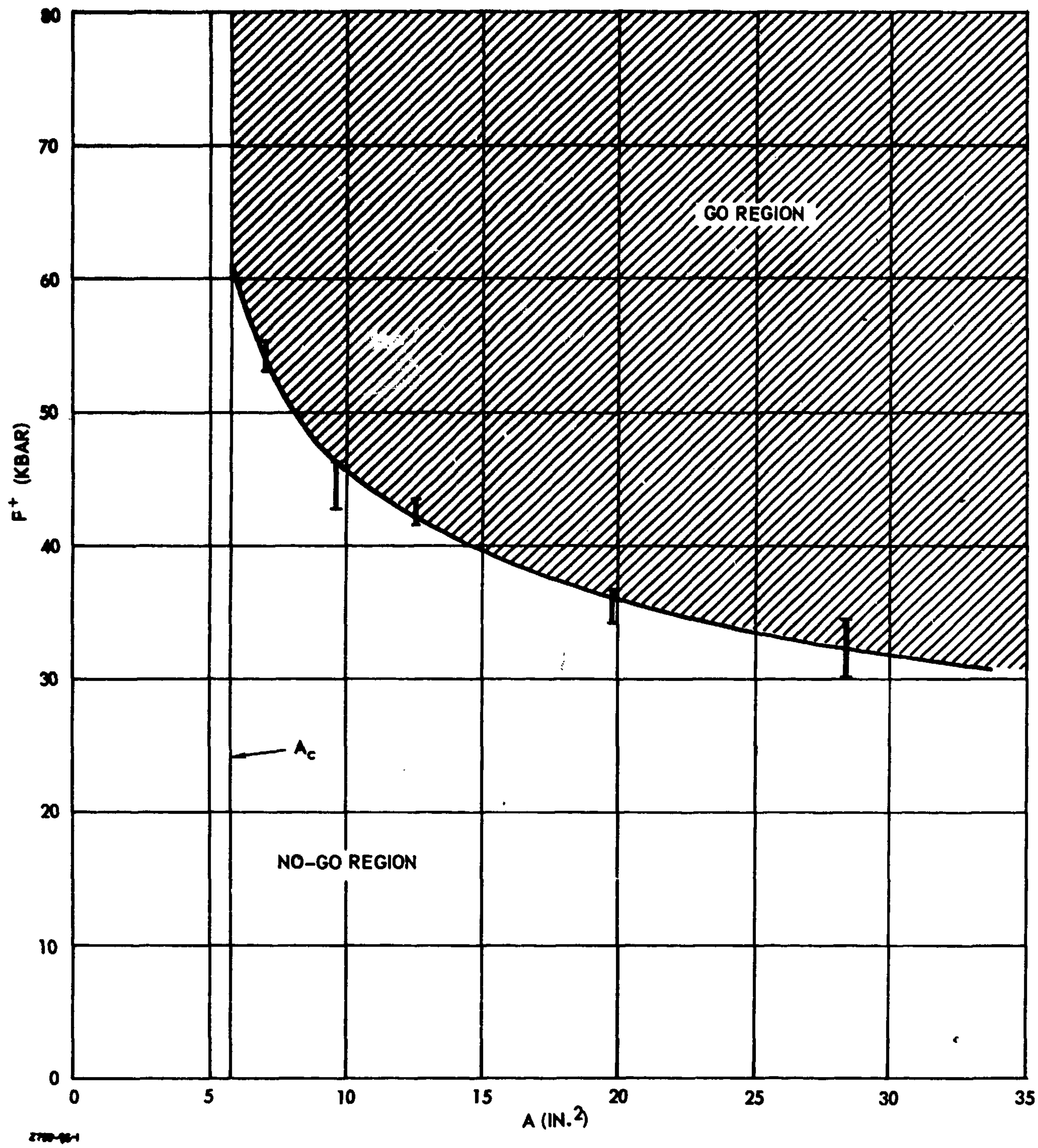


Figure 16. Initiation Criterion P^+ vs A.

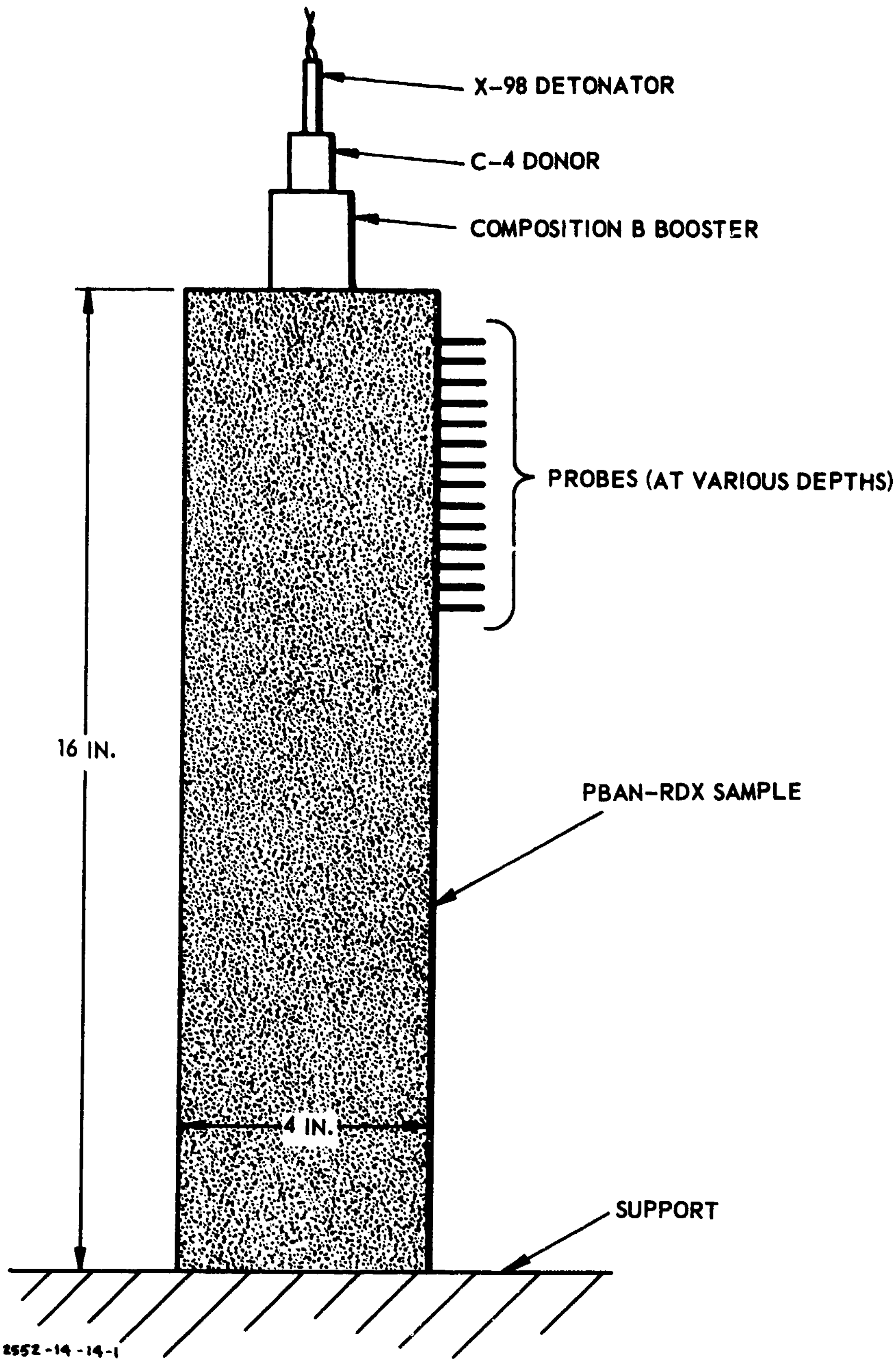


Figure 17. Axial, End Donor Test Setup for Nonperforated Acceptor.

Table VI. Axial, End Donor Tests

Test Number	Charge Diameter (in.)	Charge Density (gm/cc)	Booster Diameter (in.)	Result	Instrumentation*	Comments
1	4.03	1.730	1.0	No Go	sc/ro	
2	3.99	1.722	2.0	Go	sc/ro	
3	3.98	1.723	1.5	No Go	sc/ro	
4	3.99	1.725	1.75	--	sc/ro	Misfire
5	3.99	1.723	1.75	Go	sc/ro	

*sc = streak camera (Beckman and Whitley Model 194)

ro = rasteroscillograph (Moran and Polaroid)

Wave Diameter and Area

By assuming the waves propagate spherically and symmetrically, it was possible to use the position-time data to generate the least-squares best fit (circular) wave profiles as a function of time. The best-fit circle for each profile was defined in terms of the radius of the circle and the position of its center on the axis with respect to the booster-sample interface. From geometry and the calculus, the desired diameters and areas for each of the wave profiles were computed.

Wave Shock Pressure

Because the wave profiles are curved and the probe measurements are made only in a vertical direction, the raw velocity-time data for each insertion depth is not the true wave propagational velocity (i. e., the velocity normal to the wave front). Based on the equations of the best-fit wave profiles and geometry, appropriate adjustment factors were computed and the true velocity-time data found for each profile. From the Hugoniot of the propellant found earlier, these velocity data were converted to shock pressure.

In order to associate a unique shock pressure with any wave at any time, an average shock pressure $\bar{P}$ was defined by:

$$\bar{P} = \frac{\int_0^A P\,dA}{\int_0^A dA} = \frac{1}{A}\int_0^A P\,dA$$

where the integration is made over the entire wave surface. Knowing the equations of the circles being considered and the wave shock pressure data, Equation 16 was numerically integrated to give the average shock pressure for each wave profile.

The results obtained for wave diameter, area and shock pressure represent the desired information on the detailed attenuation process of input shock waves from an axial, end donor. It may also be noted from Table VI that the critical size of an axial, end donor required to cause detonation in this case is probably between 1.50 and 1.75 in.

Summary of the Initiation of Detonation Tests

The major objective of the initiation of detonation studies was to determine if the measured initiation criterion can be used to predict whether or not shock initiation will take place for a given booster, based on how the input shock

wave attenuates. As the initiation criterion and attenuation properties have been determined the applicability of the criterion can be tested at least for axial, end donor charges on nonperforated cylindrical acceptors. That is, it may be determined whether for this situation when detonation occurs, the initiation criterion is met or not. This was done by plotting the $\bar{P}$ vs d initiation criterion shown in Figure 15. Since the criterion might also be defined in terms of wave area, the analysis was also done by plotting the $\bar{P}$ vs A data on the P^+ vs A initiation criterion shown in Figure 16. These analyses are shown in Figures 18 and 19. Figure 18 and Table VI show that in those tests where initiation took place the initiation criterion was met (i. e, the "Go" region was entered) whereas for those tests where initiation did not take place the input shock pressure attenuation curve was such that the criterion was not met. This indicates that, at least for the situations considered, the criterion as measured (P^+ vs d) can be used to predict whether initiation will take place or not for axial, end donors on nonperforated supercritical acceptors. Also in Table VI, the average radius of curvature of the input waves is larger when initiation took place than when it didn't (3 to 5 in. compared to 0.5 to 2.5 in.). Consideration of Figure 19 shows that the criterion in terms of area did not predict the result correctly for Test 1. The attenuation curve does intersect the initiation criterion (at about 70.5 kbar) although no detonation took place in this test. However, it is noteworthy that the attenuation continues through the criterion, emerges below it at A = 9.5 in.^{2}, and stays below it for the remainder of its path. Since it is not expected that in this situation such a path is possible (i. e., entering and then leaving the "Go" region) it implies that the criterion should be shifted to the right or the attenuation curves to the left (as in Figure 18). The results of the other three tests do conform to the criterion in Figure 19. From these tests, it was tentatively concluded that the criterion in terms of wave diameter is more accurate in predicting initiation of detonation than the criterion in terms of wave area.

It may also be noted that the results with axial, end donors show that for this geometry the donor diameter need not be equal to or greater than the critical diameter of the acceptor in order for initiation to take place. In fact, in this case, the required diameter, 1.50 to 1.75 in. is only from 54 to 66% of the critical diameter, 2.66 to 2.80 in.

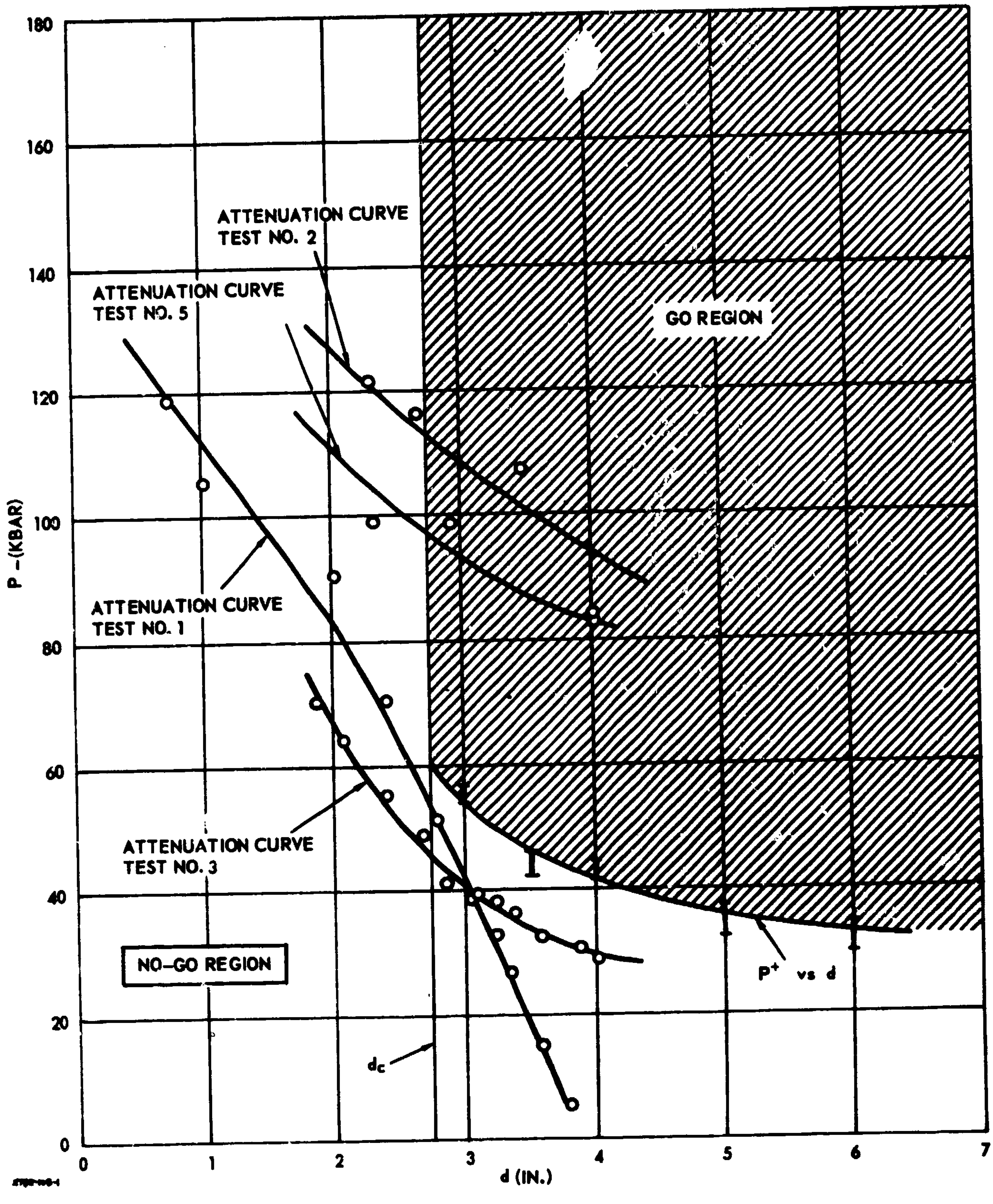


Figure 18. Test of Initiation Criterion.

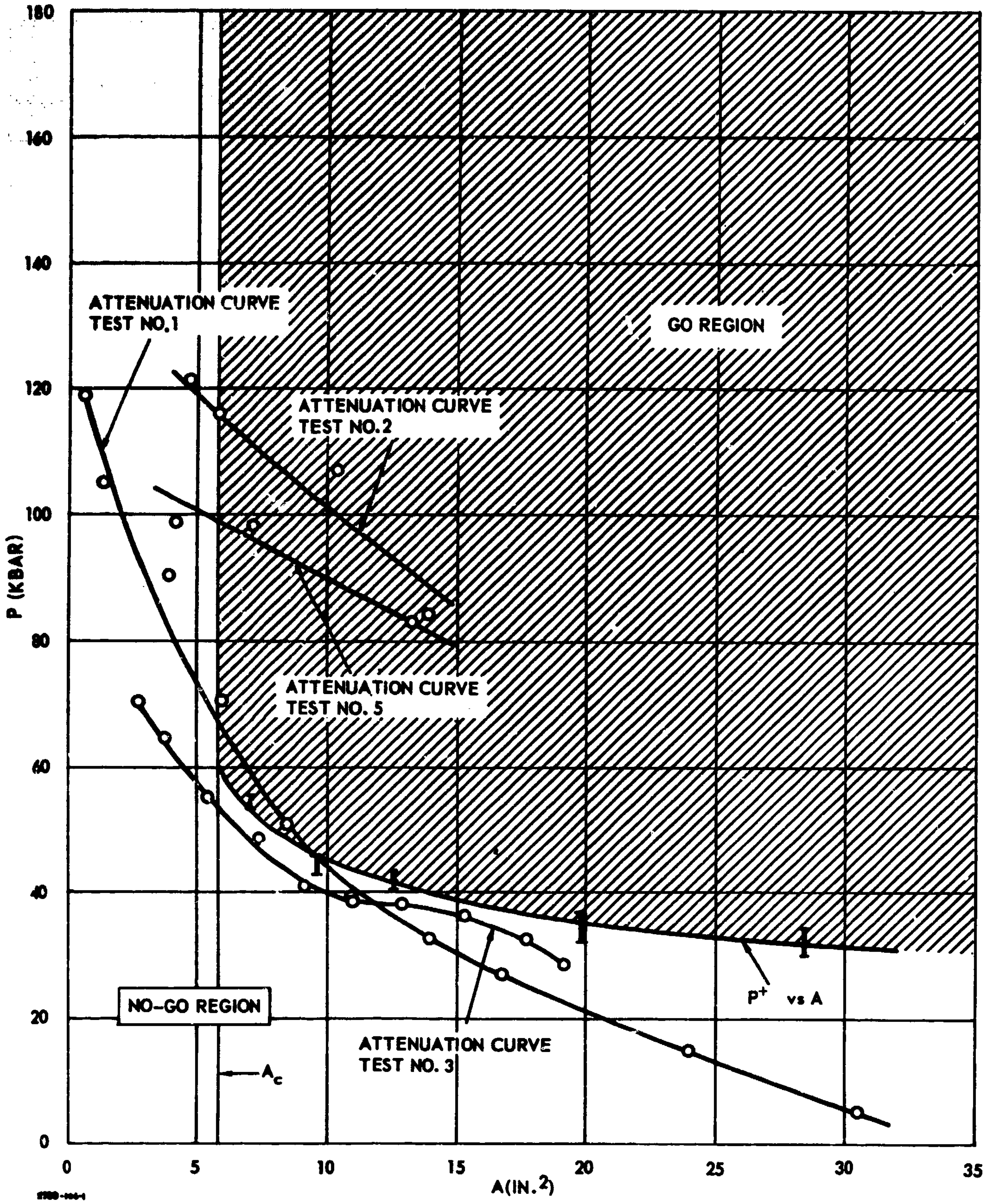


Figure 19. Test of Initiation Criterion.

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APPENDIX

CENTRAL CAVITY JETTING

When the central cavity of some preliminary circular-core cylinder tests was left empty, a jet was produced that punched the witness plate and obscured the witness-plate test result. When the cavity was filled with soil or dry casting plaster, the jet did not occur, however, no witness plate damage was apparent.

From the work of Sultanoff (Reference 5) it was concluded that the jet proceeded faster than any detonation wave produced and, because of the pressures and temperatures involved, initiated reaction on the inside wall of the cavity. This reaction proceeded normal to the "desired" detonation wave and eventually consumed the material in the lower half of the charge. This occurrence is considered possible, whether the central cavity is filled or not, since the necessary reaction need be initiated only on the inside surface of the cavity. Although the filled cavity might prevent the main body of the jet from damaging the plate, some jetting in the annular space near the fill-charge interface is expected which might initiate reaction in the material. Since this reaction is generally parallel to the witness plate, only minimal witness plate damage, if any, is expected. For these reasons, it was concluded that even when the central cavity was left empty, the witness plates were not damaged by the detonation reaction. In these cases the damage resulted from the jet only. These conclusions were supported by the preliminary test results.

A careful examination of the streak camera records for these tests showed two general types of behavior. In the one case, the reaction velocity vs distance remained steady for from 2 to 2.5 diameters and then suddenly faded to velocities well below the estimated sonic velocity of the material. In the second case, the curve simply faded rapidly without any steady portion. This behavior may be explained as follows: If the charge detonated, this wave would proceed down the charge until it was met by the normal wave. At this point, the detonation front would appear to a streak camera to fade rapidly and then disappear. Because of the geometry of this intersection, the velocity would seem to decrease continuously to zero. If the charge did not detonate, the initial wave would attenuate in the usual manner before any intersection with the normal wave occurred. Since the behavior described is precisely that recorded by the streak camera, a short section of constant velocity before the rapid fade was considered sufficient evidence that the charge had detonated. When no such section appeared, it was assumed that no detonation had occurred. This is the manner in which the preliminary test results were determined.

Because of these difficulties, it was suggested that for the propellant the effect might be relieved by (1) drilling a hole in the witness plate to coincide with the charge cavity, as a means of reducing the high pressures associated with the jet; (2) placing a metal rod in the cavity to see whether the jet formation could be prevented without providing surface confinement; and (3) using

a solid booster charge and a small amount of Plexiglas attenuator to see whether the jet formation could be delayed sufficiently to obtain better data (i. e., all other tests used a hollow core booster which helps form the jet more quickly).

The first suggestion was tried on the second circular core cylinder test where a 1.50 in. hole was cut in the witness plate. Because the 3/8 in. thick witness plate could not be found after this test and a hole was punched in the 2 in. thick support plate, it was concluded that relief of the jet pressure by this method was not feasible.

Because of the limitation on the number of available perforated samples, it was decided to carry out the remaining investigative experiments on circular-core Composition B cylinders. Using this material, one charge was tested with, and one without, a 0.5 in. diameter steel rod concentric to the cavity. The framing camera results of these tests together with the witness plate results indicated that negligible, if any, delay in the jet formation was accomplished.

The motivation for the third suggestion was based on the fact that the reaction velocity-distance data of previous tests had shown an attenuation from the high velocity booster wave ($\sim$ 7mm/μsec) to the steady detonation in the propellant ($\sim$ 4mm/μsec) and that the shock pressure required for initiation was considerably less than was actually being put into the charge with a direct booster-charge interface. For these reasons, it was felt that the use of a solid booster and a small ($\sim$ 1 in.) thickness of Plexiglas attenuator would cause initiation of the charge with a shock wave closer to the steady detonation velocity of the material. This would promote a quicker attenuation to steady-state and prevent the jet formation in the booster, thus delaying the formation of the jet in the acceptor. This was found to be highly successful and increased the amount of useful data that could be extracted before the normal wave appeared. Furthermore since it was found that there was evidence that the jet was reflecting off the witness plate and causing detonation of the charge, the data available was further increased by cutting a hole in the witness plate (not to relieve the pressure but to allow the jet to pass through without reflection) and digging a hole approximately 1 ft deep in the ground below the charge. With these improvements, the results of testing with hollow core charges became definitive.

AKST, MASON & HANGER: How much confinement if any was used and what did the denominator C, 1 over F + C - what did that denote?

VALOR: Okay, a two-part question. About the confinement; as I mentioned, the critical diameter testing was actually in two parts. First were the adulterated propellant tests where we worked from approximately 12% up to 1/4 of 1% - these had no confinement at all. The two larger tests that you saw in the movie had an 80 mill aluminum girdle around them. This was necessary because we were getting up to large quantities of propellant and were worried about the viscoelastic flow when it sat out there. As you noticed I had the cross-hatched area drawn on the slide that showed the difference between the go and the no-go, the known region. I didn't extend that to the zero percent line between the 60 and the 72 because actually we were introducing another variable which is this very small amount of confinement. Just to be on the safe side we consider it to be two separate parts, whereas the original work was just used to enable us to predict the critical diameter. The factor of C takes into account inherent porosity plus possible voids and fractures in some of the larger AP crystals which would give the same effect as one of these hot spots or initiation sites that we believe to act the same way as a small discrete particle of RDX.

KING, GENERAL ELECTRIC: Did you get any detonations with a diameter of donor less than the diameter of the propellant?

VALOR: Right. As I mentioned in the discussion of initiation criterion, I'm afraid we made the last chart a little too busy where we had the cross-hatched area and then the lines going into it. That's what it did show - that we could cause an initiation with a donor of less diameter than the critical diameter. As you saw, the shock intensity decreased as the diameter of the shock wave increased and if it did happen to reach the proper criterion it would initiate the detonation.

KING: Were the proportions, that is, length to diameter of the donor charges, maintained the same throughout?

VALOR: For the critical diameter portion, yes, they were 3 to 1.

TRESHER, VANDENBERG AFB: How far out were the metal fragments after detonation?

VALOR: On the 72" test it was hard to tell, really, because the largest pieces we found were in the neighborhood of maybe 2" of that aluminum skin. We actually couldn't find any to speak of.

LANDAU, NOTS CHINA LAKE: What percent solid loaded was the propellant?

VALOR: It was approximately 80%, off hand. That's the only thing in the program that is classified - the exact composition of the propellant.

WACHTELL, PICATINNY ARSENAL: Was any effort made to measure the explosive yield of these units?

VALOR: Yes sir. As I mentioned, our test area was instrumented very similarly to Mr. Marshall's PYRO area. We had side-on, face-on, and time of arrival gages. We did, indeed, measure overpressures, these are found in the final reports published. These ranged (we hate to use a TNT equivalency because of the difference in impulse that doesn't conform to the classical TNT curve) all the way from 200% to 100% depending on the distance from ground zero where you took the pressure and impulse reading.

WACHTELL: On the unit that was below critical diameter that threw the propellant around, have you any idea what the percentage yield was on that?

VALOR: We have some rough ideas. As I said this took place just a few days ago and we haven't really gotten it broken down yet. We'd have to subtract out the effect of the booster before we could get a real good contribution of the propellant. As you saw there was quite a violent reaction and we expect to have a very sizeable yield from it. We just have some very rough data right now.

JAFFE, NOL WHITE OAK: I'm a little interested in this factor C and I was wondering if you could tell us how you obtained some and what some of the magnitudes are?

VALOR: We noticed through microtoming of specimens, and what have you, that there were inherent voids. I think that we'll all have to admit that, probably, the state-of-the-art propellant is not 100% perfect. We noticed small voids. The biggest thing we noticed is something you can't really do too much about and these were the small cracks and voids of the AP crystals themselves, which under adiabatic compression would act the same as a RDX particle. Values for these inherent flows were run thru various analysis and computer runs and they varied from .003 on up to about .008. I think the one we have come up with here that's applicable to this propellant system which we have used as the base line for further investigations is about .0053, in that neighborhood.

JAFFE: That is the value for C?

VALOR: That is the value for C.

JAFFE: How close is this in a variation of density of the propellant that you are using? I think you probably have a closer relationship between the density of propellant and the critical diameter and possibly you can get a better correlation this way.

VALOR: You mean using porosity in place of RDX?

JAFFE: Yes.

VALOR: This was thought of at one time but we found out we couldn't control the porosity as far as orientation and/or distribution. I have to agree with you though, it is indicative of the quality of propellant in which you didn't introduce the porosity, it just happened to be there because we haven't succeeded in making propellant absolutely 100% perfect with 100% perfect constituents.

HARTON, NASA HQ: Inasmuch as the conventional critical diameter test is a confined test and these are unconfined, the question comes into my mind and maybe you have a feel for this now, what would the critical diameters be relative to your values if you had these in confined configuration? Do you think they would be less or do you have any feeling for this?

VALOR: We would expect, since what causes a detonation to fade is rare faction and the edge losses, that confinement would be liable to decrease this critical diameter. However, you remember these two tests with the unadulterated propellant did have an 80 mill aluminum skin on them which in some way simulated a flight weight skin on something! We would expect a heavier case, which would be quite a bit stronger, might tend to slightly decrease the critical diameter that we have obtained under our program.

OUTLINE OF ACTION IN THE EVENT OF AN EXPLOSIVE INCIDENT

A Panel Discussion
by

Bruce M. Docherty, R. G. Perkins, and J. E. Settles

During the course of routine operation of any plant which manufactures propellant or explosives or any military base which handles or stores propellants, explosives or munitions, there is an ever-present possibility for an accident to occur which will involve explosive reactions. This potential will exist, and it will be ever-present, despite the most rigid of precautionary safety activities. Should such an accident occur, its ultimate extent may be of major proportions. There may be loss of important facilities and injuries to workers, or even fatalities. Under these more extreme conditions, it may be that the event would be properly described by the word "catastrophe."

The potentials may be described pictorially and sequentially by the following:

A facility which looked like Figure 1 may be, in a matter of seconds, changed to look like Figure 2:

Figure 1

Figure 2

Capt. Johnson has allocated one hour of this seminar's agenda time for a review of this subject because of the far-reaching potentials of such events. In order to obtain maximum benefit from this hour, we have planned a discussion period during which important phases of the problem will be reviewed by a panel of three and there will be a question and answer period of sufficient duration to make possible, we hope, the clarification of any major uncertainties which you may have in mind. The members of the panel include Mr. Bruce Docherty, Assistant General Counsel of the Army, who will discuss the public relations and legal aspects of disaster planning; Mr. Russel Perkins, safety engineer on the Technical Staff of the Armed Services Explosives Safety Board, who will review problems associated with damage assessment; and I will serve as moderator and will attempt to give you an over-all perspective of disaster planning.

Should the daily routines of your plant or military base be suddenly confronted by an explosive accident of major proportions, certain urgent and immediate action will be required. This action will include the functioning under emergency conditions of a fire department, a medical department, a guard department, and a maintenance department. There will be urgent communications problems, both with and between field efforts which are attempting to cope with the problem, and there will be a need to communicate promptly with higher headquarters.

It can be assumed the requirements for action in the foregoing areas will be so immediate and urgent that there will be little possibility of their being overlooked. Later in this discussion period, we will review these urgent requirements in more detail. However, there are very important areas of responsibility which are not as obvious in character as the foregoing. These less obvious responsibilities can have serious potentials and because of such possibilities, we are going to give them careful consideration during this discussion period.

One area in which inadequacy in recognizing or coping with these less obvious responsibilities may bring more detrimental repercussions than deficiencies in the handling of the more urgent requirements involves the legal potentials and responsibilities which are inherently a part of such accidents. The scope of this part of the problem includes those liabilities which may develop from subsequent court actions as well as a broad field of public relations, judicious handling of inquiries from daily news media, cooperation with official investigating bodies, and the interests of the Government. We believe it will be of considerable value to this group to have an authoritative discussion of this part of our problem. Mr. Bruce Docherty, Assistant General Counsel, Department of the Army, has agreed to review some of the important aspects of these potentials.

Legal Aspects

Bruce M. Docherty
Assistant General Counsel
Department of the Army

As Mr. Settles has made clear, we are concerned today with planning for the actions which should be taken immediately following an explosive accident. I have been asked to make a few remarks about the legal aspects of such planning.

This is not an attempt to give you a completed plan, certified as to legality, which you can take home and put into effect. That would hardly be practicable. My chief desire is to stimulate thought as to the legal difficulties you are likely to encounter.

I first became aware of this problem when Capt. Johnson, Chairman of the Armed Services Explosives Safety Board, asked me to serve on this panel. The situation was not unlike that of the man who purchased a mule from his neighbor. The seller assured him that the mule was a willing worker and not in the least balky. The next morning the new owner hitched up the mule but couldn't get him to move. He yelled at him, shoved him. Nothing worked. Finally he called his neighbor over and accused him of selling a balky mule.

The neighbor picked up a huge stick and with one tremendous blow he broke it over the mule's back. The mule started forward. "You see" said the neighbor "this mule is perfectly willing to work. But you do have to attract his attention."

Fortunately Capt. Johnson's methods are milder. But he did succeed in attracting my attention. Having looked into the matter I am convinced of the importance of having a legally adequate plan for actions to be taken following a serious explosion. I believe that a careful study of the problem will lead you to the same conclusion.

Perhaps even more than my two colleagues on the panel, I am disposed to tread rather cautiously however. I have no desire to rouse the honest wrath of your house or installation counsel by trespassing on their functions. Nor can I hope to know the problems of specific companies, plants or installations as well as they. My first and most earnest bit of advice is this. Ask your own attorney to enter actively into this type of planning. Seek his approval of any plan which you adopt.

Why is legal input so important in planning of this kind? Well for one thing there is the adage that whatever you say may be used against

you. Serious explosions lead to claims for personal injury or property damage. In some instances there may even be a possibility of some criminal aspect as in certain violations of ICC regulations.

The period immediately following a catastrophe is not the best time for speculation - in public - as to causes of the accident or the allocation of blame. Nor is it always a good moment for generous, but possibly ill considered, offers to recompense those who may have suffered loss or injury.

Adlai Stevenson is supposed to have said something to the effect that a politician is a man who approaches every problem with an open mouth. From a legal standpoint it would be inadvisable to follow such a procedure in the period immediately following an explosion.

One danger is that some official will "guess" as to the cause of an accident before the matter has been fully investigated. Later information may show that he was wrong. But his statement may still be used in court against the company or the Government and might very well decide the case.

During the Seventh Explosives Safety Seminar I gave a paper on the legal aspects of an explosion. As that paper emphasized, the legal responsibility for an explosion is often shrouded in doubt. The liability of industrial concerns may vary from state to state. Similarly the Government's liability will depend on the law of the particular state where the accident or injury occurs.[1]

Both Government and contractor may be to blame. In such a situation some courts allow the entire loss to fall on whoever the injured party elects to sue. In other jurisdictions each of the responsible parties may pay a share of whatever damages are awarded. Or ultimate liability may be determined by an indemnity agreement between the Government and the contractor. Obviously the underlying legal relationships should be considered in release of information or discussions with prospective claimants.

I think it would be well to have all releases of information about an explosion channel through a single official, thus promoting consistency and reducing the likelihood of premature admissions of responsibility. This would apply to information given to the press or to representatives of the local community, as well as statements to agencies, Federal, state or local, with an official interest in such accidents. The same point of contact might also handle requests for access to the scene of the accident.

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[1] 28 U.S.C. 1346(b)

In the event of a serious off base explosion the Air Force assigns a general officer to the scene of the disaster. He becomes the single Air Force point of contact on problems arising from the explosion. He directs community relations and monitors emergency assistance. An emergency assistance team, usually including the Staff Judge Advocate and the Claims Officer, goes at once to the scene of the accident. As a matter of policy, however, these emergency activities are carried on without admission of Air Force negligence or responsibility.[2]

The question of access may sometimes be rather sticky. Just who is entitled to poke around at the scene, immediately following an explosion?

I am indebted to Lou Jezek, Army Materiel Command, for the following: There was an explosion at an Army arsenal. Promptly thereafter a television crew appeared, requesting permission to come into the installation and take pictures. The answer in this case was "No." The Army was taking its own pictures. Release would be through the Public Information Officer. Presumably that was that. But shortly thereafter a helicopter swooped down on the scene of the explosion taking pictures for a news agency.[3]

Suppose we have a privately owned, privately operated plant which does both Government and non-Government work. Is the rule of access the same whether the explosion occurs on Government or non-Government work?

Or we may have a Government owned plant, perhaps contractor operated. Or the explosion might take place on a public highway. Are the same people to be given access in every case? Or will the rules vary depending on where the explosion occurs?

Where military accidents occur outside military installations, newsmen are given maximum cooperation consistent with national security. They are asked to cooperate in protecting classified material. The military authority at the scene shall (and I quote)

> Refrain from using force if news media representatives refuse to cooperate in the protection of classified DoD material, but request...the assistance of appropriate civil law-enforcement officials in preventing compromise of such material and in recovering all photographs, negatives, and sketches which are presumed to contain classified information; ....[4] (End of quotation)

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[2] AFR 190-4, 5 April 1966

[3] See AR 360-5, 29 August 1961, para. 26

[4] DoD Directive 5410.14, October 25, 1963

The official responsible for release of information should be in a position to obtain prompt and expert advice as to what data may properly be made available. The number of persons from whom he may seek guidance would vary, presumably, with the local organization. Legal assistance and provisions for security clearance would seem to be essentials.

Every official concerned should know his function, and there should also be provision for alternates to take over if designated personnel are unavailable. Unavailability might be something of a problem immediately following an explosion.

All this may seem rather obvious, and perhaps even elementary. If that should be your reaction I can take comfort in one thought. Even though this is a seminar on explosives, this group is unlikely to revert to the original meaning of that word. As you are undoubtedly aware the word "explode" comes from the Latin "ex" meaning "out" and "plaudere" to applaud or clap. Three or four hundred years ago, to explode meant to clap and hoot an actor or performer off the stage when his presentation was not considered to be satisfactory.

Fortunately that meaning is obsolete. Emboldened by that obsolescence I will continue with a few remarks about the problem of claims.

The Government's authority to pay claims is based on statute. The military departments, NASA and AEC, although acting under different statutes, can all pay claims up to $5,000 for personal injuries, death or property damages.[5] Also by a very recent amendment to the Federal Tort Claims Act, heads of Federal agencies may settle claims of up to $25,000 under regulations to be prescribed by the Attorney General.[6]

Section 2736 of Title 10, U.S. Code may have a special bearing on the problems being considered today. There are two sections 2736 in Title 10 of the Code. It is the earlier of these, which became law in 1961, to which I refer.

In ordinary cases the military departments cannot make advance payments prior to formal settlement of a claim. Section 2736 of Title 10, however, gives the armed services special authority to make immediate payments up to $1,000. The authority is limited to cases of injury, death or property damage resulting from an accident involving an aircraft or missile. The purpose of the statute is to permit the Military Departments to give prompt assistance to those in immediate

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[5] 10 U.S.C. 2733; 42 U.S.C. 2473(b)(13); 42 U.S.C. 2207

[6] P.L. 89-506, 18 July 1966

need of food, clothing, shelters, medical treatment or other necessities as a result of a disastrous accident. It is perhaps of special interest to note that the law provides that such an advance payment does not amount to an admission of Government liability for the accident. The advance payment is deducted from the amount of any claim which is ultimately approved.[7]

The purpose of an advance payment -- to relieve immediate distress -- should be made clear. It would be unfortunate if those suffering heavy loss in an explosion should receive the impression that the object of an offer of immediate payment was to obtain a release of all liability in exchange for a relatively small payment before the full extent of the damage could be ascertained. This of course is not true.

A Government installation, in planning for a possible disaster, must pay special attention to the claims regulations of the particular agency. Prompt and efficient investigation of claims is important to preserve vital evidence. The Army provides detailed guidance for claimants, investigators, claims officers and others interested in the processing or approval of claims. This procedure includes, among other things, such matters as securing testimony of witnesses, physical examination of persons injured, and the obtaining of diagrams and photographs at the scene of the accident. There are also special areas which the report of the claims officer must cover in explosion cases.[8]

Similarly, I am sure that industry, as represented here, already has established procedures for handling claims, either by your own personnel or perhaps by insurance adjusters. And a business concern may be able to operate more freely than Government installations in such matters as advance payments or other emergency assistance to those who have suffered injury or loss. It is important, however, that any such existing procedures be followed and, if necessary, adapted to the conditions which are likely to prevail immediately following a major explosion.

Of course the Armed Services Explosives Safety Board is very much interested in accident data as an aid to improving safety regulations and preventing future accidents. In discussing the collection and analysis of such data both Mr. Perkins and Mr. Settles have some comments on the preservation of evidence which should gladden the heart of any lawyer.

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[7] See AR 27-20, 20 May 1966, paras. 38, 39

[8] See AR 27-20, 20 May 1966, Appendix

My remarks this morning have drawn chiefly on military sources. This is because such sources are readily available to me and also because time does not permit exhaustive discussion of this subject.

For example, I have spoken of a single point of contact. You might find it more desirable to handle requests from the press and from prospective claimants through different channels. I do feel, however, that all such actions should be coordinated. Similarly disaster planning of contractor and Government should be coordinated, especially where operations are closely intertwined.

When there is a serious explosion, it is apparent that the fire must be put out, production resumed et cetera. It is not always so obvious that advance planning is necessary for taking care of requests from such sources as the press, community officials or prospective claimants.

It may well be that your concern or installation already has a fully adequate plan for the actions to be taken in the event of a serious explosion. The Army Materiel Command, for example, has given its installations detailed instructions on this subject.

If your planning, however, does not give full consideration to legal aspects, I think that such an addition would be highly desirable. A disaster leads to pressure and tension. Good prior planning is absolutely essential if the actions taken following an explosion are to be prompt, effective and legally sound.

Mr. Settles (cont'd)

In planning for and coping with disasters which involve explosive reactions, the problem of damage assessment is of major concern. There will be immediate and urgent problems related to recovery of operations on a plant site; there may be off-plant damage requiring attention; there will be cost problems; there may be questions from boards of investigation and numerous other problems directly related to damage assessment. Again, we have a category of urgent items which are so obvious it is improbable their need would fail to be recognized. And again, we have a less obvious, but very important area of concern that is related to the collection and analysis of data from accidents involving explosions. Mr. Russel Perkins, safety engineer on the Technical Staff of the Armed Services Explosives Safety Board will present this portion of our discussion.

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Collection and Analysis of Data From Accidents Involving Explosions

Russel G. Perkins
Armed Services Explosives Safety Board

1. Introduction

Mr. Settles and Mr. Docherty have discussed the major local disruptive effects and legal aspects of catastrophic incidents. My remarks as a part of this panel are aimed at, hopefully, improving the value of accident data which is recorded and which can later be used to reaffirm, correct or refine existing safety regulations. This includes quantity-distance regulations, the hazard class information contained in DoD Instruction 4145.22, and many other subjects having to do with the control, as well as the prevention, of such incidents.

The purpose of these brief remarks will be to highlight items which may make the permanent record of an incident investigation a useful document that in fact has permanent value.

Forty years from now very few people will be interested in the local history at the incident site, but there may be a very vital interest in the degrees and amounts of damage done at various distances, the amounts and types of explosives involved, types of extra protection afforded, distances at which persons were killed and injured, and related hazard experience data.

2. Existing safety precautions, in particular quantity-distance regulations, are minimal and involve the acceptance of some degree of hazard. The fact that this is so requires that these regulations be as accurate and all encompassing as is possible for us to make them; yet they must be eminently practical in order to permit work to proceed. Basic safety precautions are based, in large measure, upon empirical data derived from the results of accidents. In modern times, complete dependence on data from accidents has been eliminated by increased opportunities to conduct some deliberate tests, by improved knowledge of scaling techniques which permit extrapolation from small to large scale events, and by improved ability to use statistical analyses and analogies. Notwithstanding these facts there are some situations and effects for which a full scale event of maximum credible size and in the true configuration is the only real answer to the questions which arise. In many cases, however, such full scale exact configuration tests would be completely out of the question from an economy viewpoint. It behooves us therefore, to obtain from all major incidents, as well as planned tests, a maximum amount of accurate data which may reflect information with respect to the causes of the incident and a comparison of the effects with those which might be predicted from review of existing formal standards.

3. There are certain fundamental actions, of course, which must be taken in event of a catastrophe which may be slightly antithetical to the gathering of that data which is of most interest from a safety analysis point of view. It is obviously necessary to put out fires, render first aid, recover the injured and dead, and restore utilities without delay. The performance of these actions may sometimes obscure or destroy evidence which later we wish we had preserved. After initial steps are taken to relieve the immediate effects, however, and the area can be secured, it should be kept clear, until adequate investigation can be made, of any activity which may change or destroy evidence.

4. Analysis

a. Causes of Incidents. It is recognized, of course, that the fixing of responsibility and determination of liability sometimes require considerable effort. This effort should be limited to that necessary to comply with existing laws and regulations. Determination of the cause of the accident, from the standpoint of the physical factors which brought it about and in order to prevent recurrence, is much more important than the simple finding of "who did what to whom."

b. Effects of Explosions. A large number of detonations of material have occurred in widely varying situations. The manner of investigation of these has varied almost as widely as the configurations of whatever pre-incident storage, manufacturing, or handling activity was involved. As a result, the data acquired which has been used to influence the safety precautions in the past is of widely varying veracity and value. We will publish, with the minutes of this Seminar, an outline summary of those things we think are significant to observe and record in the investigation of accidents. Some of these items are:

(1) Amount and type of explosive involved.

(2) Whether or not there were two or more explosions, and approximate time intervals between.

(3) If several buildings are involved in damage, the distance in feet to each should be given where practicable, rather than a general statement such as "15 houses were heavily damaged out to X distance."

(4) Number and type of craters for each explosion site.

(5) Particular note should be taken of accident features which are anomalous in the light of existing regulations such as extreme directionality of blast effects, severe blast damage well beyond the distance expected from the

amount of explosive concerned, and contrarywise, an extraordinarily low-level of damage to a particular building in an exposed position within the usual danger area.

I want here to emphasize the importance of recording the evidence of blast effects, fragment dispersal and damage, and other post-accident evidence of what happened. I would emphasize not only the recording, but accurate and complete recording. For instance, in the literature there exists a record of one explosion in which damage is reported as "the farthest point of structural damage was done to a house in an exposed position on a hill, at a distance of about half a mile." Note that there is no qualification as to the level of structural damage or the quality of the building which sustained it, and the distance given is an approximation.

c. Care should be exercised to obtain an accurate estimate of the maximum amount of explosive that may have detonated in a single blast. Also, if more than one detonation occurred, an effort should be made to obtain a reasonable estimate of the time between to determine whether communication was direct communication from the immediate effects of the first detonation or a "cook-off" as a result of ensuing fire.

d. A great many investigations dwell at length upon massive damage in the area of near total destruction, and some describe in gruesome detail the extent of injuries sustained by persons who were sufficiently close to the seat of the explosion to have been killed by blast effects, thermal effects, primary fragments, flying debris, or by being thrown through the air and dashed to the ground, and may, perhaps have had all five of these stimuli effecting them. On the other hand, such a report might rather lightly dismiss significant damage done just beyond inhabited building distance because it occurred to a structure not considered to be of great significance, such as a barn, inert warehouse, or unused industrial building. Accurate observation of all damage is desirable even though it might not have been significant from the standpoint of damage claims or personal injury.

e. It should be particularly noted if any unusual effects occur such as moving vehicles being struck by debris or other experience of persons actually on a highway or railroad. When unusual conditions of this nature are noted, the distance should be recorded as for structural damage.

f. Eyewitness accounts are certainly of value, but the distance and direction from the explosion for each witness should be recorded. It should also be noted whether or not the person was experienced and knowledgeable and in a position and a situation such that he could be expected to be an effective and reliable witness. The events surrounding

a major catastrophe frequently adversely effect the credibility of even the most stable and experienced of persons.

g. The importance of photographic records cannot be overemphasized. Adequate pictures, including aerial photographs, should be taken to show types and degrees of damage, spread of fragments and debris, etc. Aerial photographs to supplement maps should be acquired wherever possible in order to permit measurement of distance to targets which may not always be present or whose importance is not apparent in the early stages of the cleanup.

h. Examination of the debris frequently yields considerable information as to source location, timing of accident and so-forth. For example, if two separate explosions occurred, it may be important to determine which occurred first. If they are of equal size, this is frequently difficult but can sometimes be positively determined by the relationship of fragments from the two different sources. I recall, for instance, one test sequence in which a large steel plate which had been propelled through the air had a piece torn out of it by a second explosion. This piece was found to have been returned in the reverse direction, and came to rest on the opposite side of the event from where the plate had originally been located.

i. A very useful reference describing the investigation of fragment and debris dispersal is "The Study of Missiles Resulting From Accidental Explosions," A Manual for Investigators by Crosby Field. This was originally published in 1947 and was recently reissued by the AEC as their Safety and Fire Protection Bulletin #10. It is available for sale by the Superintendent of Documents, U.S. Government Printing Office.

j. In recording structural damage to buildings, note should be taken of the types of damage done to buildings and the degree that the different features are damaged, i.e., a simple statement that "studs were broken or rafters were broken" is not very helpful, but should be emphasized by some qualification, such as "50% of the rafters in the building were broken" or "all studs on the wall facing the explosion were cracked," as the case may have been. Moreover, the dimensions of supporting members which are broken should be reported.

5. Conclusion

In summary, I would only like to enter a plea for the maximum amount of recording of pertinent data which is generated at extremely high cost in many instances and sometimes with considerable local embarrassment, but which can be readily and rapidly lost due to improper and inadequate recording.

Mr. Settles (cont'd)

It is inevitable that there will be a multiplicity of details requiring attention, should a major disaster occur on a manufacturing plant site or on a military base. Some of these problems will demand immediate attention. It will be possible to give others more extended consideration. Regardless of the category in which any one requirement is placed, personnel assigned to that problem area should have a maximum of technical skill and competence. Advanced planning and training can provide a reasonable solution to this part of the problem.

Both advanced planning and training fall into categories of disaster planning which are not urgent in character. Their need and value may be overlooked - until the moment the disaster occurs. Because their true value and importance are not immediately obvious, it may be helpful to examine them in more detail.

Even though it is generally agreed that experience is one of the best teachers, no one wishes to experience an actual disaster. However, in order to intelligently plan in advance for such eventualities, and to train our personnel for maximum effectiveness, should the disaster occur, it can be most helpful to have realistic experience to guide us. It is believed a review of several case histories will be of benefit in considering this part of our problem.

One of the major disasters which was experienced in 1965 occurred at the Louisville, Kentucky Works of the du Pont Company on August 25th. A comprehensive review of that accident was furnished by the du Pont Company to the National Fire Protection Association and was published in the January 1966 issue of "Fire Journal," a publication of the NFPA. It was very commendable of the du Pont Company to share their experience with industry, and it may be that we can draw profitable conclusions from the details which they have supplied. The portion of that report covering the disaster control experience, both preceding and during that accident, are pertinent to this discussion. The following is quoted from the report given in "Fire Journal:"

> "There was an active, up-to-date disaster control plan in effect at Louisville, and when it was put into operation for the first time, it worked. It did not work perfectly, or in every respect, but the discipline established over years of practice resulted in personnel's reacting in an orderly manner under stress.

The Works Disaster Control Procedure had conditioned employees to the importance of head count and orderly evacuation; but it did not include provision for total plant evacuation or for establishment of an alternate control headquarters off the Works.

The head count continued during the withdrawal, and the different colored hard hats worn by each department provided ready identification of groups.

Abandonment of the Works resulted in separation of members of the plant Disaster Control Group normally assembled around the Director. It became necessary to improvise the control operation. The situation was further complicated by drastically reduced communications. Telephones were not available and important outside calls could not be made. Moreover, the county police, city police, Civil Defense, Rubbertown Mutual Aid Association, volunteer fire department, and plant radios were all on different frequencies. Communications became even worse when the control stations found the plant control group and the civil authorities located 300 yards apart.

Despite the problems, communication was maintained by runners, mobile equipment, and a pair of police cars stationed at each control center to make use of the police radio channel coordinating the plant control group and the civil authorities."

The foregoing experiences of the du Pont Company emphasize that even with careful planning and practice, it is very difficult to anticipate the realistic and demanding requirements of the real emergency. It follows that if planning is superficial and training is cursory in nature, that the problems and difficulties which will be experienced when the real thing occurs will be appreciably magnified.

It is extremely difficult to anticipate the physical and the emotional impact of experiencing a major disaster. For example, when you have an existing structure which, at a particular moment in time, looks like Figure 3, and five seconds later it looks like Figure 4, the magnitude of the problems which will confront you, instantaneously, are extremely difficult to appreciate or anticipate. These pictures are the "before" and "after" scenes of a disaster which Hercules experienced at Allegany Ballistics Laboratory on April 26, 1963. Our problems at that time were additionally magnified by the fact that the accident occurred at night and during the same instant that the buildings disappeared, a major portion of the plant lighting system, was knocked out. The deficiencies of emergency lighting sources are most impressively understood under such conditions.

Figure 3

Figure 4

Disaster planning is one of the mandatory activities of Hercules Explosives and Chemical Propulsion Department, and practice on simulated disasters is a regular part of the activity. At no time have any of our disaster teams engaged in a simulated disaster without deficiencies in our disaster planning being revealed. These deficiencies have included such faults as failure of an automatic signal system; failure to notify the Maintenance Department; failure of the designated person to take charge at the disaster location; deficiencies in segregating the disaster area; slow response time of various units of the disaster team; and numerous others.

Some additional examples may improve your appreciation of this point.

It can be anticipated that maintenance crews will be confronted with numerous and unusual demands, should a major disaster occur. However, in attempting to instruct and train maintenance crews in the realistic aspects of the problem, it is very difficult for them to appreciate that the real emergency may look something like Figure 5.

Training in the establishment of the proper road blocks around a simulated disaster area can be relatively calm and deceptively simple in practice, as is obvious in Figure 6.

However, when the real thing occurs, the adequate segregation and control of an area like Figure 7 is considerably more complicated and difficult.

It is highly desirable to have your doctors, nurses, hospital staff and ambulance drivers conduct simulated disaster runs, such as is pictured in Figure 8.

It can be assumed that the real emergency will be accompanied by much more demanding conditions. If the patient on that stretcher is badly burned or is suffering massive bleeding, the requirements are much more demanding.

A fire department on a simulated disaster exercise will find it an interesting exercise to attach their hose lines and spray water on an existing and unaffected building. This picture shows the comparative calm of such a practice exercise. (Figure 9)

However, the surrounding terrain and conditions associated with a real disaster will be appreciably different and the accompanying problems will be of a much different magnitude. The following picture will give an impression of how firemen may be operating in case of a real disaster (Figure 10).

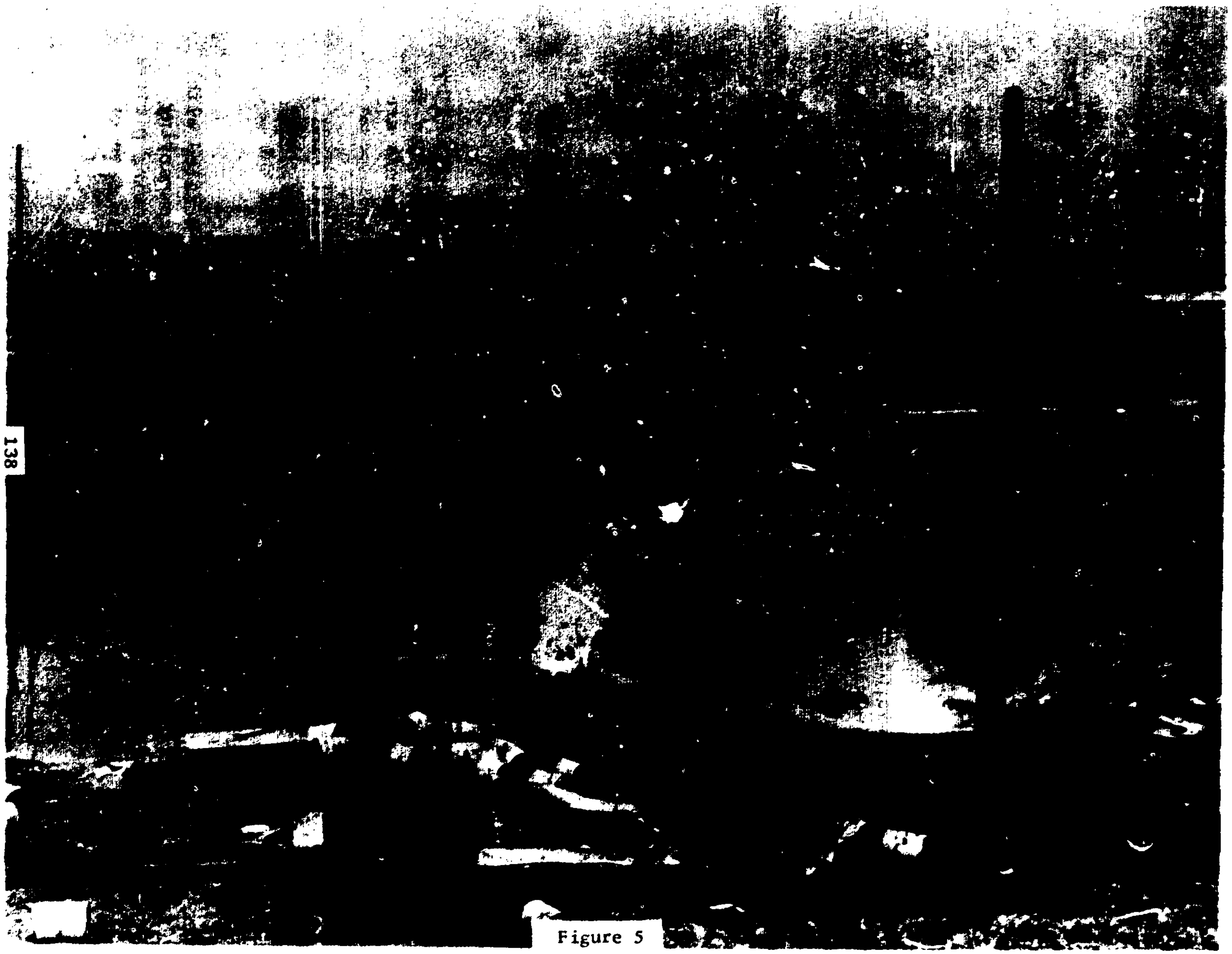


Figure 5

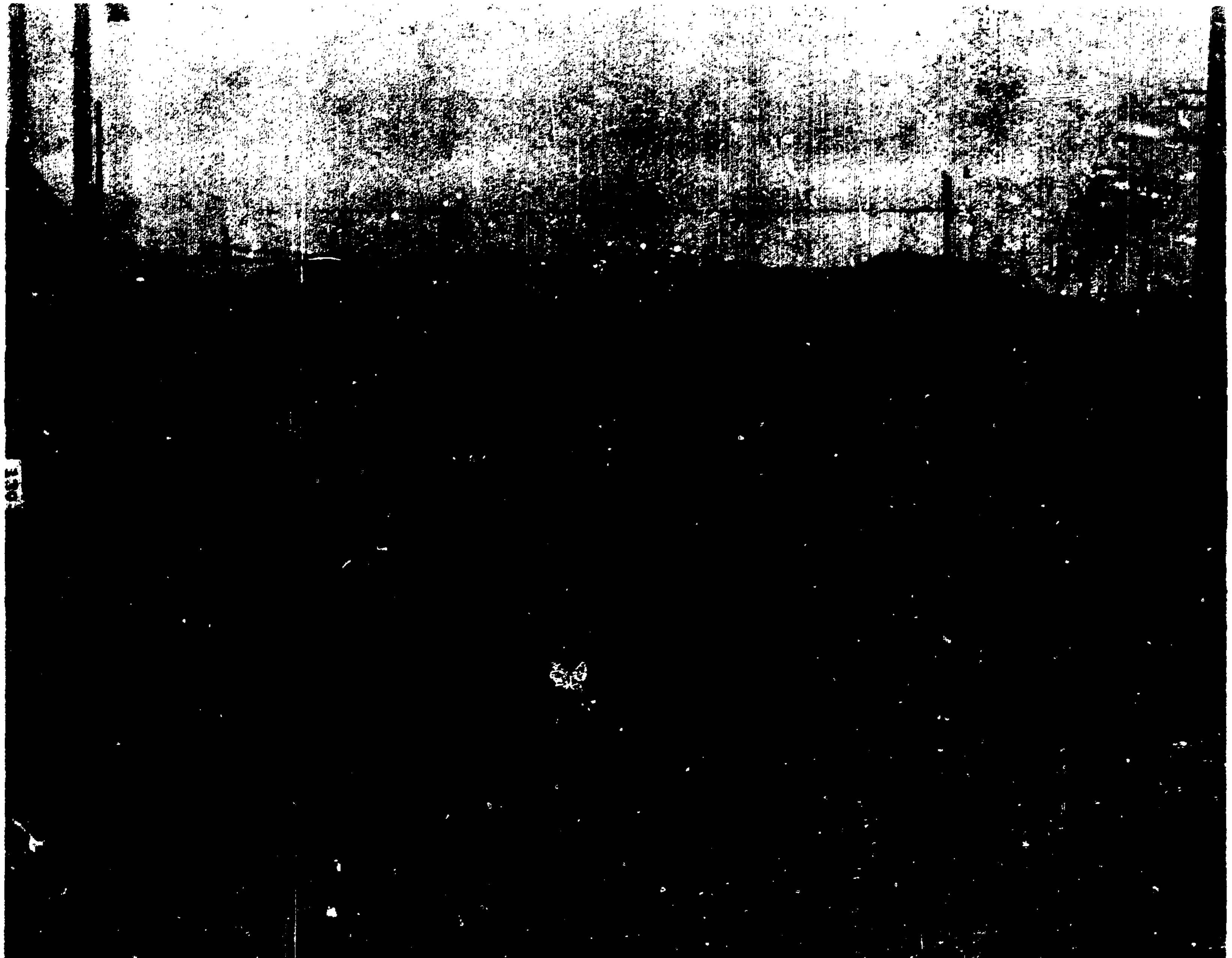
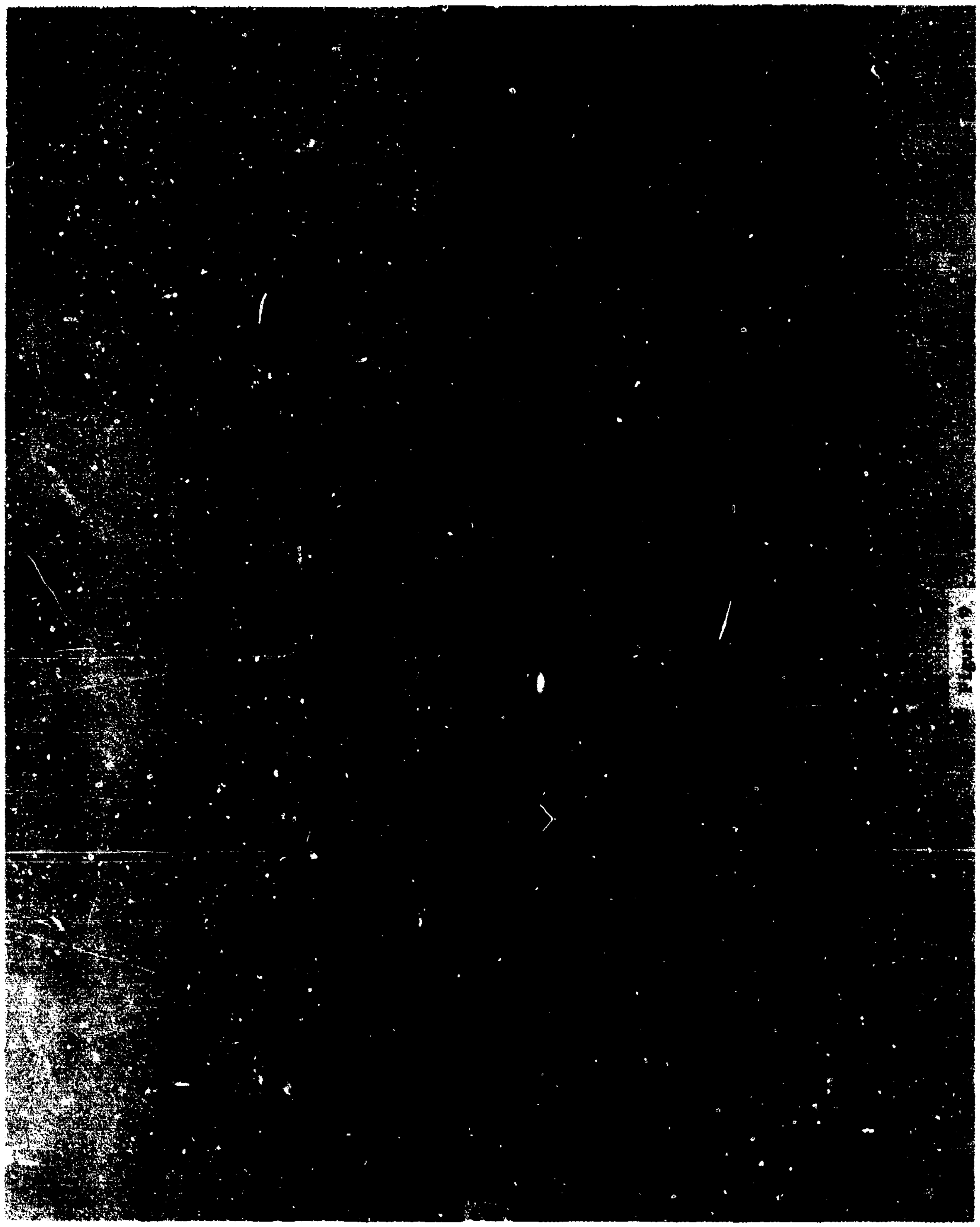


Figure 6

Figure 7

Figure 8



Figure

Figure 10

The foregoing pictorial review has been presented to point out the differences between disaster practicing and the real thing. However, it cannot be emphasized too strongly that training and practice are vital parts of preparing for such emergencies. It is certain that deficiencies in planning and lack of perfection in execution will be encountered when the real emergency occurs. However, these inadequacies will be greatly magnified if practice and training have not been a part of the preplanning effort.

The ASESB allocated one hour of their agenda time to this discussion because of the obvious importance of this type of planning. It is not possible in this hour of time to present more than the important requirements of disaster planning. Covering the details would require more time than is available here. For example: The Army has announced a special course on Industrial Defense and Disaster Planning for privately-owned and privately-operated facilities to provide executives in industry and Government with a working knowledge of the principles of disaster planning. The Army's course runs for five days.

It may be helpful to present and discuss briefly the major points of disaster planning which are required by pertinent documents of the Department of Defense. Those points which have been stressed during this discussion period will also be summarized.

A vital function associated with most major disasters will be the overall control of activities. Normally, a commanding officer or a plant manager will have this responsibility. The complexity of the problem, the urgency of decisions, and the multiplicity of details demanding immediate attention make difficult a judicious and objective perspective and further emphasizes the need for a well organized approach. Experience indicates the problem can best be handled by utilizing a Master Control or Command Station which normally would be the point from which a Commanding Officer or a Plant Manager would control the situation and which will be located somewhat remote from the actual disaster scene. Rapid communications are vital to the effective functioning of the Master Control Station and it must be adequately equipped and staffed. Without a doubt, a commanding officer or plant manager will visit the actual disaster scene at intervals; however, most of his time will probably be spent in the Master Control Station.

There will also be a need for a continuous command function at the scene of the disaster. This will be necessary in order to effectively coordinate the efforts of the various groups that will be active at that point. In addition to the standard requirements of accounting for all personnel, prompt care of the injured, guarding against spread of fire and control over entry to the area, there may

be a potential for additional explosions to occur. Some personnel working at the disaster scene may not be aware of such potentials and, without guidance, may unjustifiably expose themselves to such hazards.

A fire department obviously will have demanding responsibilities in case of any disaster. Where explosives are concerned, it may or may not be desirable to attempt to fight any fires. However, there will be problems associated with the major fire itself and there may also be a potential for a fire to spread to surrounding facilities. If the scope of the disaster is beyond the capabilities of the facility firefighting organization, it may be desirable to request the services of outside firefighting agencies. In addition to these prime responsibilities, it may be necessary for firemen to assist in administering first aid to the injured, to aid in the evacuation of personnel from the area immediately affected, and to assist in the rescue of injured or trapped persons.

The medical department associated with a particular facility may not be staffed with personnel or equipment adequate to meet the demands associated with a major disaster. Under such conditions, the obtaining of outside medical assistance may be necessary. Severely injured personnel may require transfer to adequately staffed hospitals in the adjacent areas. Additional duties of the medical department will be to administer appropriate temporary treatment to injured personnel; it may be desirable to check all employees from the affected area for possible injuries before they are permitted to leave the reservation; and the medical department will, of course, keep abreast of the progress of patients sent to the outside facilities.

The guard department should be prepared to not only segregate and control access to the area which is immediately affected by the disaster, but also to maintain effective control within the establishment of personnel and vehicular traffic beyond the affected area. Access to and egress from all areas will be in compliance with instructions issued from the Master Control Station. A prime responsibility of the guard department will be to protect the disaster scene from all unauthorized disturbance until official investigations have been completed. It may be necessary for the guard department to request assistance from state and local enforcement agencies in order to control traffic on highways approaching the installation.

A prime responsibility of the maintenance department will be to eliminate the hazards of broken electric, gas, steam, and water lines in the immediate vicinity of the disaster, and the maintenance department may find it desirable to anticipate the impairment of these services, should there be a spread of the disaster to adjacent areas. It may be necessary to provide equipment for handling or removing heavy debris

in the rescue of the injured or trapped personnel. And resumption of normal utility services at the earliest possible time should be a part of maintenance concern and planning.

The transportation department should be prepared to furnish transportation for auxiliary firemen guards and to furnish upon request, appropriate transportation to effect necessary movement of personnel and material.

The legal aspects of plant disasters and also the problems associated with public relations have been reviewed by Mr. Docherty. The public relations problems will include news releases to authorized news media, certain obligations to the families of the injured, and advise on the progress of recovery activities to the plant work force.

Mr. Perkins has covered the problems associated with post accident investigation and the value of their accident investigation analyses. In addition, there should be personnel available at the scene for the specific and exclusive purpose of recording all pertinent factual conditions associated with the occurrence. Competent personnel should be assigned to contact and interview as promptly as possible all available eyewitnesses in order to secure initial impressions. The establishment of the identity of casualties promptly and positively will be important. There will be a need to photograph pertinent exposures and to assist the duly appointed officers and representatives of authorized investigative agencies.

It just may be that the most profitable part of this hour's discussion to you will be to answer a question which you have in mind. We are now ready for questions to the panel. You may, if you wish, direct a question to a specific member of the panel or you may ask questions which are general in scope and we will decide which of us will answer. If none of us feel competent to answer, we will ask for help from experts who are present, or we'll ask for opinions from the floor.

SUGGESTIONS FOR INFORMATION TO BE COLLECTED AFTER EXPLOSIONS

Supplement to Panel Presentation

1. The following outline suggests details of information to be obtained and actions to be taken which will preserve valuable data for inclusion in later studies to determine if existing safety precautions and quantity-distance regulations are adequate. Certain items of information may not apply in all cases and the sequence of investigation may not be in the listed order depending upon individual circumstances.

a. Examination of Scene

(1) Prevent disturbing of debris. Changes in location of important objects or removal of them by souvenir hunters may effect the conclusions reached by investigators.

(2) Locate the seat of the explosion or incident and indicate whether or not there was more than one center of major activity. Define, if possible, the actual point of origin and the sequence of events if more than one center of fire or explosion occurs. Determine:

(a) Conditions which existed just prior to the explosion and what process was involved.

(b) If more than one explosion, the distance between, protection between, and time interval between.

(c) If there was no communication, distance to and protection afforded nearest explosives.

(3) List the hazardous materials involved. This should include all high explosives, propellants, solvents, etc. Chemical composition, amount, physical location and state of manufacture should be given to the extent this is available. The net amount of high explosive involved is a very important piece of data and should be accurately recorded. If several different kinds are involved, the separate amounts should be shown for each.

(4) List crater dimensions for each explosion site. Crater information is an important parameter related to explosive weight. If no other means is available, it is sometimes helpful in judging the amount of material involved in the incident. In this respect it is important to distinguish between the "apparent" crater depth immediately evident and the actual depth, taking into account the amount of "fall back" into the crater after the incident.

(5) Persons Exposed

Number and exact location of all persons at the time of the incident should be shown. A single casualty looms large in the accident report but the number and position of survivors may be of greater importance in determining the degree of hazard from the event. Particular note should be taken of instances in which some type of protection, either by chance or design, saved a person from death or serious injury when this person might normally have expected serious effects.

(6) In all cases of damage note should be taken of any directional effect because of an elongated charge or reduction of damage due to orientation of buildings.

(7) Radius of complete destruction.

b. Examination of Surroundings & Remote Effects

(1) Radius of structural damage beyond economical repair. This should also include information as to the number and type of buildings in this category and summary information as to the extent of damage which caused the decision. If this radius is based on one building which was of poor quality and is reported without this detail it can be quite misleading. Special economic or emergency factors prevailing at the time of the incident may also influence a decision as to whether or not to repair a building. If a large number of buildings are involved, attempts should be made to categorize them as follows with numbers in each category:

(a) More than 75% demolished.

(b) Those requiring immediate demolition to remove immediate hazards from collapse.

(c) Large buildings of which portions only are severely damaged.

(d) Any remaining partially demolished buildings.

(2) Radius of Repairable Structural Damage

(a) This should include listing by specific buildings of the types of damage done and distance in sufficient detail to enable later evaluators to assess the data and come up with meaningful conclusions. For instance, don't say "studs broken" and let it go. Indicate size of studs, material, spacing and number.

(b) Where information can be obtained, roof and main support members damaged in walls facing the blast should be treated as distinct from those on side or rear walls. Also, for example, a statement such as "75 houses were heavily damaged to a distance of 1500 feet" is much more meaningful if one is given information as to how many houses were at or near the maximum distance and how many were at significantly lesser distances rather than the simple statement quoted.

(c) A summary of all claims for damage which were justified and paid should be included with the permanent records with notes as to the distance of each from the incident.

(d) Note should be taken of undamaged buildings between the explosion site and damaged buildings. If only a few of a group of buildings are damaged the percentage that are damaged should be shown.

(3) <u>Range of General Glass Breakage</u> (if applicable)

This should be reported in a manner which shows the extent of such damage. A single isolated instance of glass breakage at a huge distance may be of local interest at the time of the incident and may be costly to repair. It may also, however, be of very little technical value if most windows between that point and the radius of repairable structural damage survived the explosion. When a large amount of glass breakage occurs, as in a city complex, some assessment should be made and reported as to the difference, if any, between walls facing the incident and side or back walls. It should be determined, if possible, whether broken glass was thrown entirely across rooms, embedded in opposite walls, or just broken and dropped near the window. Noteworthy instances of penetration of food stores, furniture, packaged liquids or similar items should be recorded.

(4) <u>Fragment and Debris Dispersal</u>

(a) Distance to which most fragments and debris were projected and the kind and weight of fragments should be recorded. Secondary fragments such as pieces of buildings or other surrounding environment may give considerable information about the events of the incident by their size, range, and orientation. Also, the effect of these missiles upon objects struck should be noted.

(b) The concentration of fragments at appropriate distances from the seat of the explosion should be given in terms such as the number per thousand square feet, specific area per fragment, or other definite means showing a relatable quantity which can be

correlated with other information reported by other investigators for other incidents. Note should be taken of fires set by hot fragments or burning embers. If secondary explosions occur, note should be taken as to whether or not they occurred instantaneously or after a preceding fire. When fixed ammunition, projectiles, or other ammunition items may be projected from a pile, the area should be checked to determine if secondary explosions of these have occurred upon impact.

(5) Injuries.

In addition to casualties immediately at the scene, cause of injury or death should be reported in those instances involving personnel who were at near intraline distance or greater in such a manner that casualties can be distinguished as having been caused by:

(a) Direct blast effects.

(b) Partial collapse of buildings.

(c) Missiles or debris from the seat of the explosion.

(d) Flying glass or other objects not from the seat of the explosion.

(e) Translation of the persons themselves by blast effects as, knocked downstairs, thrown off roads in autos, etc.

2. Any investigation of an explosion incident should include, as a part of the permanent record, a sketch to scale, showing the locations of pertinent features discussed above. This sketch should also show locations of barricades, trees, hills, or other terrain features which may have had an influence in either intensifying or reducing some of the effects of the explosion. Personnel who prepare this sketch should be briefed on the pertinent quantity-distance regulations and the source of the incident should be related to them in such a way that other evaluators will know how many targets were exposed at or near the permitted distance for the source quantity of explosives involved. If the amount involved at the source was significantly less, or greater than permitted by the quantity-distance tables for the source, this fact should be noted.

3. Possible Causes

In many instances the immediate cause of an incident may be an "act of God" or other unpredictable occurrence that could hardly have been foreseen and avoided. In many past cases, however, incidents have been caused by failures or circumstances that might be avoided in future similar situations. In investigating accidents, careful review should be made of:

a. Records on maintenance of equipment, tools, and process machinery to detect if there had been any unauthorized modifications, undue wear or other material failures which may have caused the incident or increased its severity.

b. The health records of plant employees may be important if personnel failure appears as a factor. If personnel with physical weakness or disability, or emotional instability contributed to the incident, the findings in this respect should be made part of the record.

c. Similarly, the state of experience and training of operators should be reviewed. Inexperienced personnel, or personnel not completely instructed in the requirements of new assignments have frequently contributed to serious catastrophes in the past.

4. Witnesses

Attempts should be made to obtain the testimony of all witnesses who were in a position to observe anything of interest with respect to an incident. Care must be exercised, however, that the character, experience, knowledge, and situation with respect to the incident, of the witnesses are such that they are effective and reliable. Discrepancies in testimony that are not accounted for at the time of the original investigation can probably never be resolved long after the fact.

5. To briefly summarize the above, explosives safety regulations and quantity distance tables are heavily dependent upon information gleaned from past accidents. In order to make reports meaningful, accurate, and effective, the investigators of accidents should be alert to preserve the maximum possible amount of pertinent data from such incidents.

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UNDERGROUND SILO TESTING

by
B. M. Rosenfeld
NIKE X Project Office

During the summer of 1963, a test program was initiated by the NIKE-X Project Office to determine the environmental effects which might be expected should an accidental detonation of a SPRINT missile be experienced within an underground launch cell or silo as it is commonly known.

The purpose of the program was twofold:

(1) To obtain data to be utilized in the design of missile system structures to be located in the proximity of the launch cell, and

(2) To obtain information to determine the safety distance from the launch cell to buildings occupied by the general public.

The aspect of safety distance or Inhabited Building Distance became an important economic factor upon the conception of the NIKE-X Anti Ballistic Missile system because of necessary proximity to populated areas and consequent high cost of real estate.

The usual method of determining Inhabited Building Distance for explosives is by entry to the tables contained in the Army Materiel Command Safety Manual, AMCR 385-224. Based upon extensive experience, these tables have been compiled to determine the distance at which, should an accidental detonation occur, a building and its inhabitants would be exposed to not more than an acceptable level of risk from the primary effects of blast overpressure and flying debris.

Intuitively, a buried cylindrical launch cell provides more protection than an above-ground barricaded structure; so it was contemplated that a

reduction in the distance required by the AMC Safety Manual should be possible as a result of testing.

A test program was drafted with the assistance of the AMC Safety Division and presented to the Armed Services Explosives Safety Board for review and approval. Participants in the program included the Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland, as consultants of overpressure measurements and the Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, as consultants for cratering and ground motions.

The finalized program consisted of two, one-half linear scale tests and one, full-scale test.

Two half-scale tests and one full scale test were conducted at Redstone Arsenal, Alabama, on 18 January 1964, 18 September 1964, and 4 November 1965. All tests were conducted by the Test and Reliability Evaluation Laboratory, Research and Development Directorate of the Army Missile Command, under the direction of the NIKE-X Project Office.

The explosive medium utilized for the first half-scale test was TNT. SPRINT propellant was used for the subsequent tests. The test utilizing TNT was intended for a calibration shot in the event of a future change in the SPRINT propellant. Approximately 625 pounds of explosive were used for each half-scale test and approximately 5,000 pounds for the full scale test. In each test, the explosive was configured and located to conform with location of the SPRINT missile motors as they will be mounted in a tactical launch station.

Early in the SPRINT development program, the debris problem was recognized. This was a significant factor in the choice of steel rather than concrete for the SPRINT launch station. The launch station used for the half-scale tests consisted of 4 feet diameter by 16 feet deep cells constructed of 3/4 inch thick A-441 steel plate. The full scale cell was 8 feet in diameter, 32 feet in length, and was constructed with 3/8 inch thick A-36 steel plate. Appended to the full scale cell was a steel compartment approximately 5 feet wide by 4 feet, extending to 8 feet below the surface of the ground. All cells were mounted on a concrete foundation. Backfill consisting of red clay was carefully controlled to assure the same degree of compaction as that of the surrounding insitu soil. Cell covers were utilized in each test. Covers were fabricated of 1/4 inch A-36 steel for the half-scale test and 1/4 inch fiberglass for the full scale test.

To obtain overpressure vs. distance curves, overpressure gauges were stationed on two primary radial lines extending to 400 feet from the launch station. The distance was increased to 800 feet for the full scale test. Both piezo electric crystal and diaphram type gauges were used. These gauges were mounted to measure side-on overpressure. Ground shock was measured by means of Reed Gauges and tri-axial accelerometers. Although changes in the launch station design between the half and full scale test profoundly influenced results because of the inclusion of the compartment in the full scale test, it was possible to correlate results

between tests and draw certain conclusions. Comparisons were based upon results of the first half-scale test utilizing TNT and the full scale test utilizing SPRINT propellant. In each of these tests, both stages of the missile were detonated simultaneously. The second half-scale model test which utilized SPRINT propellant was detonated from the top second stage downward with the appropriate stage separation being maintained. In this test, the lower stage did not experience a high-order detonation; therefore, both overpressure, crater and debris results were of a magnitude considerably reduced from those of the other tests.

Test data obtained from TNT surface detonations, conducted by the Ballistics Research Laboratory, indicate that at the Inhabited Building Table Distance for an above-ground barricaded structure containing the nominally listed amount of explosives, an overpressure of approximately 1.3 pounds per square inch will be experienced. On the first half-scale test using TNT, an overpressure of slightly over 1.3 psi was experienced at 50 percent of the barricaded distance. The full scale test results indicated an overpressure of 1.3 psi at 450 feet or approximately 65 percent of the 685 feet inhabited building distance required for above-ground structures. This relative increase from the half-scale results is attributed primarily to the difference in blast effects between TNT and SPRINT propellant. Some increase is attributed to the change in design of the cell.

The debris pattern resulting from the half-scale tests indicated that the vast majority of debris, both metallic and earth, fell within one-half

of the barricaded distance. The debris resulting from the full scale test exhibited a highly directional aspect, a comparatively high percentage of both earth and metallic debris was deposited in the direction in which the launch preparation equipment compartment had been appended. In this direction, a considerable number of metallic debris fragments was deposited beyond 450 feet. One fragment was recovered at a distance of 1,400 feet. For the cell perimeter with earth immediately in direct support, both metallic and earth debris were well contained within a radius of 450 feet. For the SPRINT launch complex design, it is proposed to utilize this directional aspect and orient the launch preparation equipment compartment in a direction in which the inhabited building distance is not a governing factor.

From the tests, it was concluded that, with proper design, an underground silo or launch station will afford comparable protection to barricaded inhabited buildings at a distance which is considerably less than that specified by the tables contained in the AMC Safety Manual. Depending upon the characteristics of design, this distance may approach a reduction of one-half of the distance so specified. Other than the blast equivalency of the explosive or propellant involved, over which the designer ordinarily has no control, the following aspects should be considered in the design of a silo or launch cell. The lowering of the center of gravity of the explosives has a beneficial effect upon reducing the inhabited building distance both from an overpressure and debris standpoint. A higher density construction material such as steel will tend to

limit the number of debris fragments and will allow a more precise control over the debris pattern. A reduced diameter at the upper portion of the silo or launch cell with adequate earth confinement is desirable. A cell cover exhibiting a relatively high degree of confinement is also considered advantageous. Protuberances which cause discontinuity of earth containment around the silo should be avoided.

PRELIMINARY REPORT OF INCIDENT
AT HERCULES
CARTHAGE, MISSOURI - JULY 14, 1966
by J. E. Settles

At approximately 12:25 on the afternoon of July 14th, a fire was observed in a trailer parked near the truck loading dock in the magazine area of the Hercules commercial explosives plant at Carthage, Missouri. This fire resulted in a series of detonations, explosions and fires which, during the next 24 hours, caused destruction of a major portion of the plant and multi-million dollar damages. One fatality and a number of injuries occurred during this series of incidents.

Regrettably, my report on this incident at this time must be incomplete, and I probably will be unable to answer all questions to your complete satisfaction, for three reasons:

First, to accurately and completely establish the sequence of related events for an incident of this magnitude is a time-consuming effort in which many details must be minutely examined and related to one another. This incident occurred only a little over three weeks ago and the gathering of pertinent facts has not been completed.

Second, the destruction and damage to facilities was of a magnitude which resulted in pertinent records being destroyed, scattered or severely scrambled. We are having to depend upon human memory to a major extent to establish the movement of materials on the day of the accident and the quantities and types of explosives which were at various locations. A number of discrepancies remain to be resolved.

Third, in a catastrophe of this magnitude, certain legal complexities are inevitable. Opinionated or unsubstantiated statements could result in compromise of the company's position. Obviously, I am reading this report to you, and I am not authorized to depart to any extensive degree from this prepared script.

However, an incident of this magnitude is, inevitably, of major interest to the industry. The sharing of pertinent facts may save lives and may prevent others from suffering similar experiences. The Hercules management was most willing that this preliminary report should be given to this year's ASESB seminar. And, if it is desired, a more complete report will be given at next year's meeting. By that time, most of the present

uncertainties and complexities should have been resolved. Photographic coverage of the details of the incident has been extensive and will be available at that time. Our own photographic staff has approximately 500 still pictures and 3,000 feet of color film. Professional and amateur photographers in the area have hundreds of additional still pictures and black and white film coverage which show both aerial and ground views of the progress of the event. Any time opening which is available in next year's seminar can be devoted to details of this catastrophe.

First awareness of trouble was when a fire was observed in a trailer parked in the vicinity of the truck loading dock in the magazine area. No tractor was connected to the trailer, nor was there a tractor any where in the magazine area at the time. No personnel were near the trailer where the fire was first observed. The trailer first observed to be on fire was loaded with smokeless powder which was to be used as an ingredient in a slurry explosive. This is smokeless powder which was originally granulated for military use. At some time in the past, it was declared excess to military requirements and was sold as surplus. The history of this particular truckload of powder has not been completely established at this time. We [illegible] studying other potential sources of ignition; however, it is possible that some portion of this load of smokeless may have spontaneously ignited. Such a spontaneous reaction is plausible if its content of diphenylamine or other stabilizer were depleted by decomposition products during years of stora[illegible] Until additional studies are completed, no further comments about the i[illegible]ation of the incident are appropriate at this time.

A trailer positioned at the truck loading dock was being loaded with 60% extra gelatin dynamite by three men. Other trailers were spotted in the area, some empty, and some loaded. Because of loss of records and some discrepancies in recollection, exact quantities and locations have not been positively established. It is known that among these trailers some contained nitrocarbonitrate explosives and some slurry explosives, in addition to the dynamite.

The fire in the trailer of smokeless powder was extensive before it was noticed by the three workmen. They immediately ran from the area. The Power House operator received several calls in a short period of time about the fire and sounded a plant-wide alarm. During an ensuing 15 or 20 minute period, the fire spread to adjacent trailers and during this period of time, the major portion of the plant employees were evacuated.

At approximately 12:47 p.m. a detonation occurred, and it presently is believed to have originated among the burning trailers. During the next ten minutes, a number of additional detonations or explosions occurred, each involving major quantities of explosives. One person's estimate of the approximate time intervals between the successive explosions was as follows: 15 seconds; one minute; 10 seconds; one minute; and 5 minutes. It is estimated that approximately three-quarters of a million pounds of explosives were involved in these reactions during this ten minute interval. During the next hour, two more smaller shots occurred, and at 3:45 p.m. another major detonation took place. It was quite apparent this detonation occurred in three trailers which were being loaded with nitrocarbonitrate and ammonium nitrate - fuel oil explosives. No high explosives, such as dynamite, were permitted in this particular area. Approximately 17 hours later, three additional detonations took place.

The general geographical area had been without rain for 35 days, and temperatures of around 100°F had been common. Foliage both on the plant and in the surrounding areas was in tinder-dry condition. The spread of fires from burning fragments projected by the detonations was rapid and extensive on-plant and to some extent, off-plant.

Off-plant damage by fire was minimized by the quick and effective response of several dozen fire companies from surrounding communities. The local sheriff's office, state and local police, and the National Guard responded to the emergency quickly and effectively and provided the necessary control over the inevitable movement of people toward the disaster scene. It was approximately 24 hours after the first fire was discovered before it was judged safe for plant personnel to re-enter the area for damage assessment.

Although it will be several months before the work of collecting and analyzing pertinent data is completed, some preliminary observations may be of interest:

The effectiveness of trees in reducing blast damage appears to be greatly exaggerated.

The advantages of a complete earth cover over buildings which are to be used for processing or storing explosives was impressively demonstrated in this catastrophe. Construction which utilizes a complete covering of earth has at least three advantages which would have appreciably minimized the

severity of results in this accident. First, the blast damage which an earth-covered structure will sustain as a result of a detonation or explosion at an adjacent location is appreciably less than if the protective design is less complete. This fact also has been impressively demonstrated in the ASESB tests at Naval Ordnance Test Station during the last four years. Second, spread of fire from an explosion or detonation by means of hot or burning fragments penetrating the roof area of adjacent structures is almost completely eliminated. Third, the spread of fire from burning underbrush or foliage into a structure which is completely earth-covered is very difficult, and the possibility is much greater that such fires can be fought without unacceptable hazard and risk to personnel.

The Carthage incident has prompted us to make a careful review of how trailers which haul explosives are constructed. A pertinent point is this: Some trailers are insulated and some are uninsulated. In the uninsulated trailers there is only a very thin piece of aluminum or steel between the packaged explosives and the sun. Now correlate this consideration with this fact: We have been told by representatives of the Air Force that tests have been run on the temperature profile which will exist within the wing and fusilage enclosures of aircraft sitting out in the desert sunshine. They report that an external temperature in the vicinity of 120°F can result in internal temperatures of as high as 350°F. You will recall that this summer has been marked by a profusion of 100°F temperatures, and higher, all across the nation. Within Hercules, we are looking for answers to two questions: First, what is the difference in the profile of internal temperatures between insulated and uninsulated trailers; and second, what is the effect on the stability of a particular explosive if it is subjected to repeated exposures to such temperatures?

One last observation: It appears at this time - and on the basis of incomplete data and incomplete analysis - that the maximum extent of structural damage as a result of blast overpressure is a 1-1/2 mile radius around the Carthage plant. The maximum extent of window breakage as a result of blast overpressures appears to be a 5-mile radius around the plant.

BISHOFF, AMC: Can you discuss the relationship of these trailers, how close they were together?

SETTLES: Not very completely, Fred, because of discrepancies in verbal information. The three boys who were working in that area during that day, regretably, differ on what they thought had transpired. We're just not sure. I would rather not try to estimate because I could well be wrong.

UNIDENTIFIED: What kind of propellant was in the trailer?

SETTLES: Of course the trailers were loaded with various things. There was 60% extra gelatin dynamite in the one where the three men were actually working. Some of the adjacent trailers contained nitrocarbonitrates. At some time in the reaction, the nitrocarbonitrates were consumed in a high order reaction, a detonation. There were some that contained slurry explosives. The slurry explosives only burned.

UNIDENTIFIED: I meant what kind of propellant started the original fire?

SETTLES: We are not even sure where the fire started. As I say, it is thought that the fire was first observed in a trailer which contained smokeless propellant.

UNIDENTIFIED: What kind of smokeless?

SETTLES: That I am not prepared to discuss at this time. I'm sorry. It may be a factor of importance. That's the reason why.

LANDAU, NOTS: Could you elaborate on the fatality, such as where the person was and what type of injury he sustained?

SETTLES: I can to a certain extent. The one fatality was a man who was working in the magazine area. He had the same warning as everyone else. We believe the last that he was observed, he was still in that area and was apparently fighting brush fires. The plant manager himself had gone into the area and had ordered everybody out of it. Just where this man was during this interval, we don't know. By the way, the plant manager in giving these warnings, was almost caught by the first detonation. I estimate he was from 400 to 600 ft. away, depending upon where the first detonation occurred. He dived behind a tree. That tree was his only protection for the entire 10-minute sequence of high order events. And I estimated just roughly that he probably was exposed to around 10 psi overpressure at this particular location; although I'm not sure of that yet. I just made a rough calculation.

KOMOS, DCAS: I was there the day after the explosion. I wonder if you would care to elaborate on the one injury as to how he was found and who found him, in violation of the local orders there?

SETTLES: I would prefer not to elaborate on that. I appreciate the interest in it and next year, we will give you full details, if you so desire. Right now things are a little too tenuous in that area to get into postulations and trying to reestablish what happened. Folks may differ with my interpretation of it.

HERSHMAN, WYLE LABS: May you give us the approximate dimensions of your plant?

SETTLES: Al, it was about 1200 acres but I'm not sure of that. The first time I ever set foot on the plant was after this accident occurred.

CHELKO, NASA: Did your plant manager suffer any ear damage, has he felt any ill effects from this?

SETTLES: No, he did not. Other than a few days later he said "I believe my ears are sore." He could still hear pretty well and there was nothing of surprising nature.

CHELKO: No chest pressures or anything of this kind?

SETTLES: No sir.

TRACY, NORTH AMERICAN AVIATION: Can you talk a little about the evacuation techniques and procedures and physical conditions of evacuating a number of people like that under these kind of conditions?

SETTLES: Yes sir, I can. Everybody ran like hell. I don't mean to be facetious about this, most of them actually did move out promptly and rapidly. It was apparent from the very start that this thing was of a magnitude that you didn't tarry around and try to contain it. So they did get out and we're real glad that they did.

BISHOFF, AMC: You seem to be interested in the amount of overpressure that a human could withstand. Some years ago the Army Surgeon General caused a search of the literature. This revealed that a human could withstand 10 to 15 psi without organic injury. The overpressures may throw the individual to the ground and he would suffer injuries from contact with the ground, but no organic injury was expected from 10 to 15 psi.

SETTLES: I've heard that too Fred.

BISHOFF: When you compare this with 3 to 4 psi which will practically demolish a building, you can appreciate how wonderful we human beings are.

SETTLES: Very resilient in our construction. Dr. C. S. White out at the Lovelace Foundation in Albuquerque is an authority. I believe Dr. White estimates that the threshold for fatalities in humans, that is just pure blast overpressure, eliminating tumbling and that sort of thing, is about 100 psi. We never place our remote control shelters that are to house humans closer than the 50 psi radius. The upcoming meeting with the New York Academy of Science in October has Dr. White on the agenda. He may have some real interesting information on this subject.

WIUFF, DCAS: First you said the trees didn't do any good, what would that poor manager have done without his?

SETTLES: You sure have a point there Carl. Whenever you're in that sort of a predicament, any mass of material you have between you and the reaction is very much appreciated.

CARROLL, TROJAN POWDER CO.: How was the nitrocarbonitrate packaged?

SETTLES: I can't say for sure. However, let me make a point and this is a controversial point. The detonation that occurred at 3:45 pm was in three trailers that were loaded with nitrocarbonitrates and ammonium nitrate-fuel oil. Within the industry it has been assumed that the possibility of transition from simple burning to detonation of these particular materials is very questionable. But so far, we feel positive that there were no high explosives, boosters or initiators in these three trucks. But they sure went high-order. There wasn't any question about that and I have some good color film footage of the craters to prove it.

JEZEK, AMC: Isn't it packaged in paper bags?

SETTLES: I'm not sure. I think, normally, it is but in these particular trucks, I'm not sure how it was packed.

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CASE HISTORIES OF RECENT ACCIDENTS

by
Louis Jezek
U.S. Army Materiel Command
Washington, D. C.

I. Subject: Fire in Propellant Rolling Operation

Description of Operation: Pads of rolled propellant are prepared in the pad bay and are heated prior to being transferred to the evenspeed rolling mill in the adjoining bay. This transfer is made thru a pneumatically operated door controlled by a foot pedal in the evenspeed bay. The door has an interlock so that the evenspeed mill will not operate when the door is open. After milling, the finished sheet is transferred back to the pad bay through the same door. It is then picked up by a "buggy boy" and transported to the slitter and carpet rolling machine.

Details of Occurrence: During rolling operations a fire occurred in the evenspeed mill. The operator ran from the evenspeed bay. He then turned right, which placed him in front of the door of the adjoining pad makeup bay. At this time the fire apparently propagated from the evenspeed bay to the pad makeup bay. One operator, who was in front of the transfer door in the pad makeup bay, was seriously burned. The evenspeed mill operator in the doorway of the pad bay received burns over 25% of his body. A "buggy boy" next to the fatally burned operator received second and third degree burns. A second "buggy boy" was at the far end of the bay and escaped with minor injuries.

Number and Nature of Injuries:

1. Fatal - one. The employee making pads in the pad room was fatally burned.

2. Injured - three. One operator in the pad bay and the evenspeed mill operator were hospitalized with burns. A "buggy boy" in the pad bay received minor burns.

Causes:

1. Direct cause: Accidental ignition of X8 propellant in the evenspeed milling machine.

2. Indirect causes:

a. The deluge system failed to function in sufficient time to prevent propagation of the fire to the adjoining pad makeup bay.

b. The transfer door was defective and allowed the fire to propagate.

Remarks:

1. There were approximately 390 pounds of propellant involved.

2. The severity of the fire was increased due to propagation from one bay to another through a defective transfer door.

3. Evacuation routes from the building either were not established or the evenspeed mill operator failed to follow them.

4. A local audible alarm system and a manually activated deluge system could possibly have alerted the personnel in the adjoining bay and controlled the fire.

Recommendations:

1. Pads of propellant should be transferred around the dividing wall rather than through a transfer door. Reference paragraphs 505 and 1723b, AMCR 385-224.

2. A written fire plan should be prepared and posted to include the following:

a. Procedures for orderly evacuation of personnel and drills to all employees to use these procedures. Reference paragraphs 1230a and 1206a, AMCR 385-224.

b. Alerting, by alarm system, of all personnel in nearby activities in the event of an incident. Reference paragraph 1230b, AMCR 385-224.

c. Deluge systems with both manual and automatic activating provisions using light sensing devices to decrease activation time. Reference paragraph 1229, AMCR 385-224.

d. Checking the effective operation of fire doors or other means of confining the fire. Ref para 1206a(6), AMCR 385-224.

3. Openings in fire walls should be protected in accordance with NBFU Pamphlet No. 80. Ref par 505, AMCR 385-224.

4. The sequence of operation and personnel should be arranged so as to constitute the smallest exposure to any one explosion or fire hazard. Ref par 1601 and 1701, AMCR 385-224.

Fig. 1. Transfer door in closed position
as viewed from evenspeed bay.

Fig. 2. Transfer door open, as viewed from evenspeed bay. Operator has foot on pedal which opens transfer door.

Fig. 3. Interior of pad bay looking west. Heating cabinet is shown in center left. Bicycle buggy used to transfer finished sheets from the pad bay to the slitter is shown in the lower right. Table at lower left is copper clad with hot water coils underneath and is used to warm pads prior to placing them in heating cabinet. Transfer door which cannot be seen is on the far side of the heating cabinet.

II. Subject: Explosion and Fire in HIBEX Base Grain Transfer Operation

Description of Operation: HIBEX base grain casting propellant powder was being dumped from fiber drums into a metal hopper. The powder then flows automatically from the hopper into a drop plug buggy. The flow is controlled by a rubber diaphram peristaltic valve. A sensing element closed this valve when the desired height of powder in the buggy was reached. The entire operation was remotely controlled. The powder was then transferred to another building for blending and glazing.

Details of Occurrence: The equipment was checked, and the drums of powder were positioned on the dumping racks. The operators retired to the remote control shelter. The control switch was activated and shortly thereafter an explosion occurred, followed by fire. The fire spread to a truck containing 2,400 pounds of casting powder; approximately 30 minutes after the first explosion, the contents of the truck exploded. This truck was parked adjacent to the loading dock of the building.

Nature and Number of Injuries: Injured - three. Three members of the firefighting crew sustained minor injuries.

Causes:

1. Exact cause - unknown.

2. Probable cause - ignition of casting powder by friction, impact, or electrostatic discharge.

Remarks:

1. The casting powder (which contained a small percentage of Zirconium) generated finely-divided dust during the dumping operation. For this reason, the humidity in the building was controlled to reduce the possibility of initiation by electrostatic discharge.

2. A free fall of 14 feet from the inverted drum to the bottom of the buggy existed. Tests conducted with this type of propellant indicated that a 7-inch fall could cause initiation.

3. The metal hopper used in the dumping operation, although badly mangled, was found some distance from the original site. This would indicate that the initial explosion occurred beneath this hopper and probably in the vicinity of the valve. No identifiable valve parts were recovered.

4. In addition to the powder on the truck and approximately 800 pounds at the dumping operation, there were approximately 1,100 pounds in Bay No. 5 in a buggy. There were two drums containing a total of 78 pounds on an elevator and 6 drums (900 pounds) were positioned on a platform near the loading docks.

5. Testimony revealed that some difficulty was experienced with the diaphram valve. This valve was slow in responding or was not functioning as desired. Lights on the control panel (located in the remote control shelter) indicated this condition. Although reported, no action had been taken.

6. Property damage (including several tractor-type tow vehicles parked in close proximity to the transfer building and clean-up operations) amounted to $615,000.

7. The remote control shelter was not located at intraline distance from the operating building. This shelter was approximately 62 feet from the building. The control panel in this structure was blown from the wall and damaged extensively. This damage was probably caused by the second explosion. The 6 men in the shelter left after the first explosion occurred.

8. On-call maintenance personnel were not aware of nor were plans available to indicate what action should be taken to disconnect electrical utilities leading into the disaster area.

9. Just prior tc the explosion, a ground check on the conductive floors indicated a 5 meg ohm reading in several areas.

Recommendations:

1. The quantity of explosive material in or around the operation should be reduced to that amount necessary for safe and efficient operations. Reference paragraphs 1601a and 1602, AMCR 385-224.

2. Explosives limits should be carefully analyzed and established based on the need at the operation and not on the amount permitted by quantity-distance requirements. Ref para 1601b, AMCR 385-224.

3. Static grounding for process equipment and floors should meet the requirements of Section 7, AMCR 385-224.

4. Remote control shelters for operations involving known process explosion hazards should be located at barricaded intraline distance from the operating building. Ref para 2622c, AMCR 385-224.

Fig. 4. View shows truck dock and crater where truck was located.

Fig. 5. Southwest corner view of building showing jeep and train of drop-plug buggies.

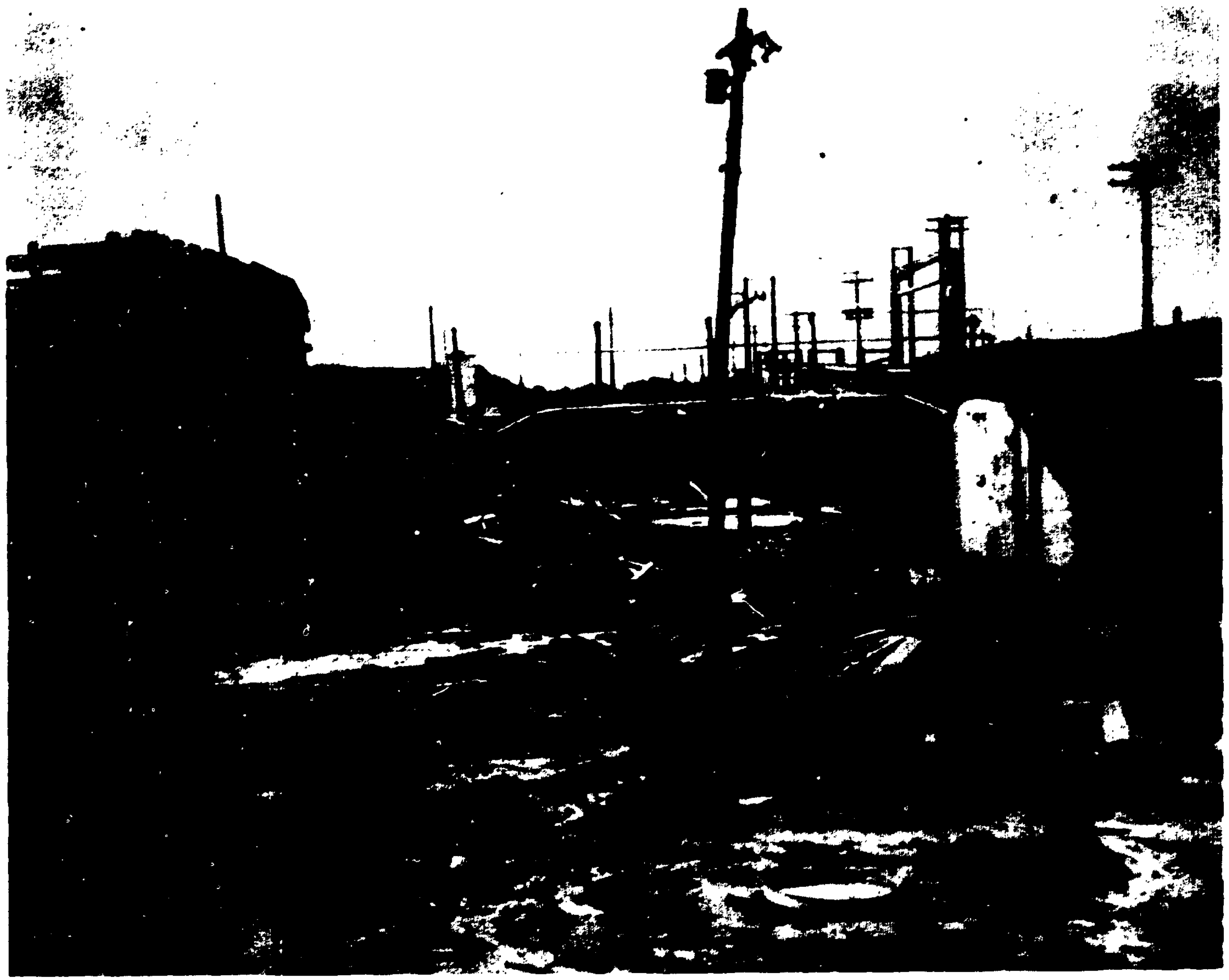

Fig. 6. View of control house and east and north sides of barricade of Bldg. 1605.

Fig. 7. Overall view taken from east side of building. Debris in the foreground is part of the steel support structure.

5. The standing operating procedure should be revised to reflect the sequence of operations, explosives limits (outside quantities included), vehicle restrictions and required tests, i.e., static grounds, humidity, exhaust and electrical controls. Ref par 1625a, AMCR 385-224.

6. An adequate local disaster plan should be developed to anticipate explosions and to fulfill the disaster plan objective outlined in par 402, AMCR 385-224. Ref par 401.

7. Operating supervision personnel should investigate malfunctions of equipment, reported to them by their employees, which might lead to an accident. Ref par 109, AMCR 385-224.

8. Height of free fall of subject propellant should be reduced to a minimum, commensurate with process equipment physical dimensions.

9. Motorized vehicles should be prohibited in close proximity to the building during actual dumping operations. Ref par 2203e(3), AMCR 385-224.

III. Subject: Fatality During Testing on a Firing Range

Description of Operation: Two operators were assigned to observe the impact location of a 105mm HC Smoke Shell fired down range. The position taken by the observers was outside the bombproof with one employee inside a vehicle and the other in front of the vehicle. The impact on the recovery field was approximately 400 meters from the observers.

Details of Occurrence: A total of 107 rounds had been fired as described above. Upon functioning of the 108th round, the employee in front of the vehicle heard a metallic ping. He turned and saw the man in the vehicle slumped forward in the passenger seat. He immediately proceeded to his aid and noticed a deep wound in the vicinity of the neck. An ambulance was summoned and the injured man was removed to the post hospital.

Nature and Number of Injuries: Fatal - one. The employee hit by a shell baffle plate was killed.

Causes:

1. Direct cause: Neck wound caused by the baffle plate from a 105mm H.C. Smoke Shell.

2. Indirect cause: Failure of the employee to take shelter in a hazardous situation.

Fig. 8. Overall view of area showing relation of bombproof to location of parked vehicle.

Fig. 9. Interior view of vehicle cab. Hole in roof indicates point of entry of baffle plate.

Remarks:

1. Investigation revealed a hole in the roof of the vehicle 4-3/4 inches long and 1/8-inch wide.

2. The baffle plate (2.96 inches in diameter and .1196 inches thick) travelled approximately 800 meters and acted similar to a buzz saw in cutting a hole thru the vehicle roof and gashing the victim's throat and chest.

3. The Standing Operating Procedure did not specify that shelter was required for the observers during this part of the test firing.

Recommendations:

1. Where there is possibility of fragmentation during firing, all personnel within the danger zone should take cover. Ref par 2821, AMCR 385-224.

2. Observation from a bombproof should be made indirectly by mirrors, periscopes or other suitable devices. Ref par 2821c, AMCR 385-224.

3. In test programs requiring the use of projectiles loaded with expelling charges or with high explosives, observers should be stationed in a protected place. Ref par 2824, AMCR 385-224.

4. Standing Operating Procedures should be revised to include the mandatory provisions of section 28, AMCR 385-224 pertaining to test programs.

IV. Subject: Explosion of Bomb, Fragmentation BLU 26/B

Description of Operation: The fully assembled bombs are brought to the assembly building in cardboard boxes packed 25 bombs per cardboard tray, 75 bombs per box. The bombs are removed from the tray and placed in canvas bags which are in a wooden tote box. When the tote box containing 3 bags is full, the box is transferred to an assembly room where the bomb dispenser is loaded. The canvas bags are lowered into the dispenser by means of a heavy cord. When the bag touched bottom, the bombs are dumped into the dispenser by means of a second cord secured to the bottom of the bag. After approximately 45 bombs have been emptied into the dispenser, the operator leaves the area and remotely vibrates the dispenser to settle and to pack the bombs. This procedure is repeated until the dispenser is full.

Details of Occurrence: Two operators assigned to the assembly room were in the process of filling the canvas bags (as described above) when an explosion occurred. The explosion was followed by fire, thereby causing additional bombs to explode.

Nature and Number of Injuries:

1. Fatal - two. Both operators in the bay were killed as a result of the explosion.

2. Injured - none.

Causes:

1. Direct cause: unknown.

2. Indirect causes:

a. Detonation of an armed M219 fuze.

b. Dropping or mishandling of a bomb.

Remarks:

1. Operating and supervisory personnel had not been instructed in safe handling techniques for this bomb.

2. Emphasis was being placed on increasing production.

3. The subsequent fire caused numerous other explosions, thereby preventing firefighters from entering the area.

4. An armed M219 fuze had been found in a lot previously shipped to the installation.

Recommendations:

1. It is recommended that M219 fuzes be X-rayed. (Items already in dispensers need not be X-rayed because arming of the fuze after being loaded into the dispenser appears to be remote.)

2. All personnel should be instructed in safe handling procedures for the item involved. Ref paras 109 and 110, AMCR 385-224.

3. Ammunition should not be handled roughly, thrown about, tumbled or dropped. Ref par 2008, AMCR 385-224.

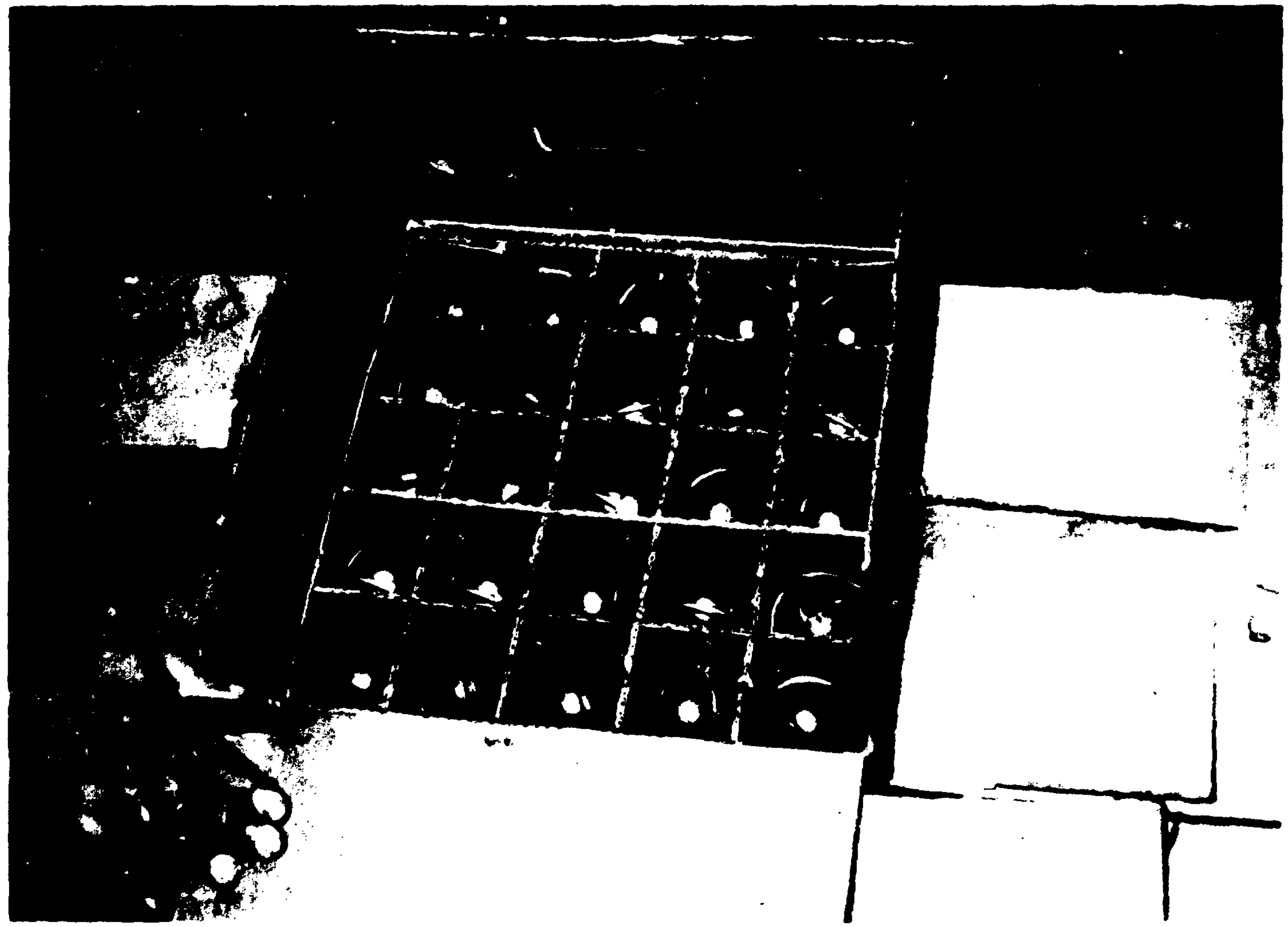

Fig. 10. Bombs in cartons on float as received in building.

Fig. 11. Composite view of alternative position of operators at the time of accident. White line is reconstructed pellet trajectory from holes in carton and east wall.

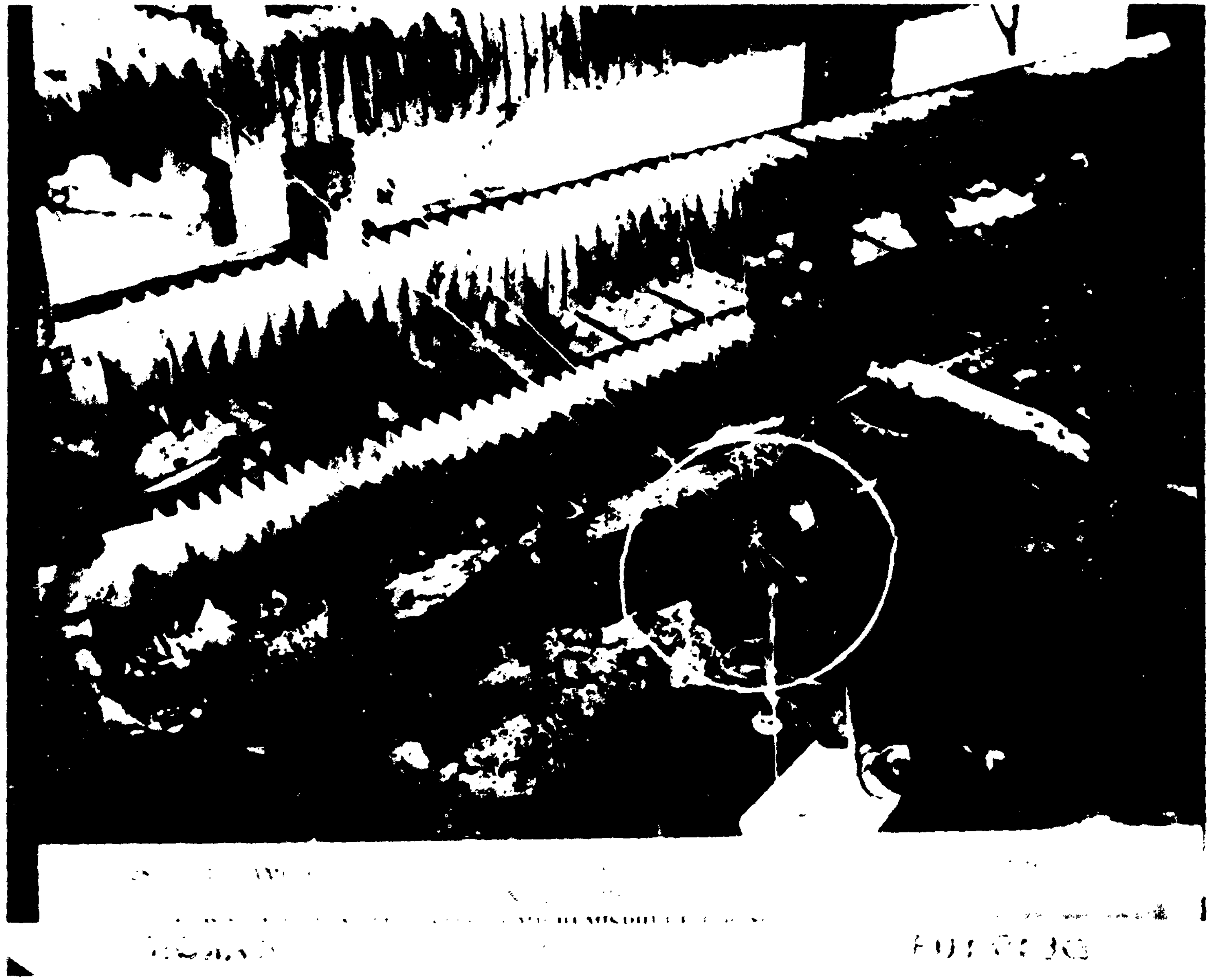

Fig. 12. Point of detonation with bomb hemisphere for scale.

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ACCIDENT SCENE ... FROM WEST

A Materiel

Fig. 13. Accident scene from west.

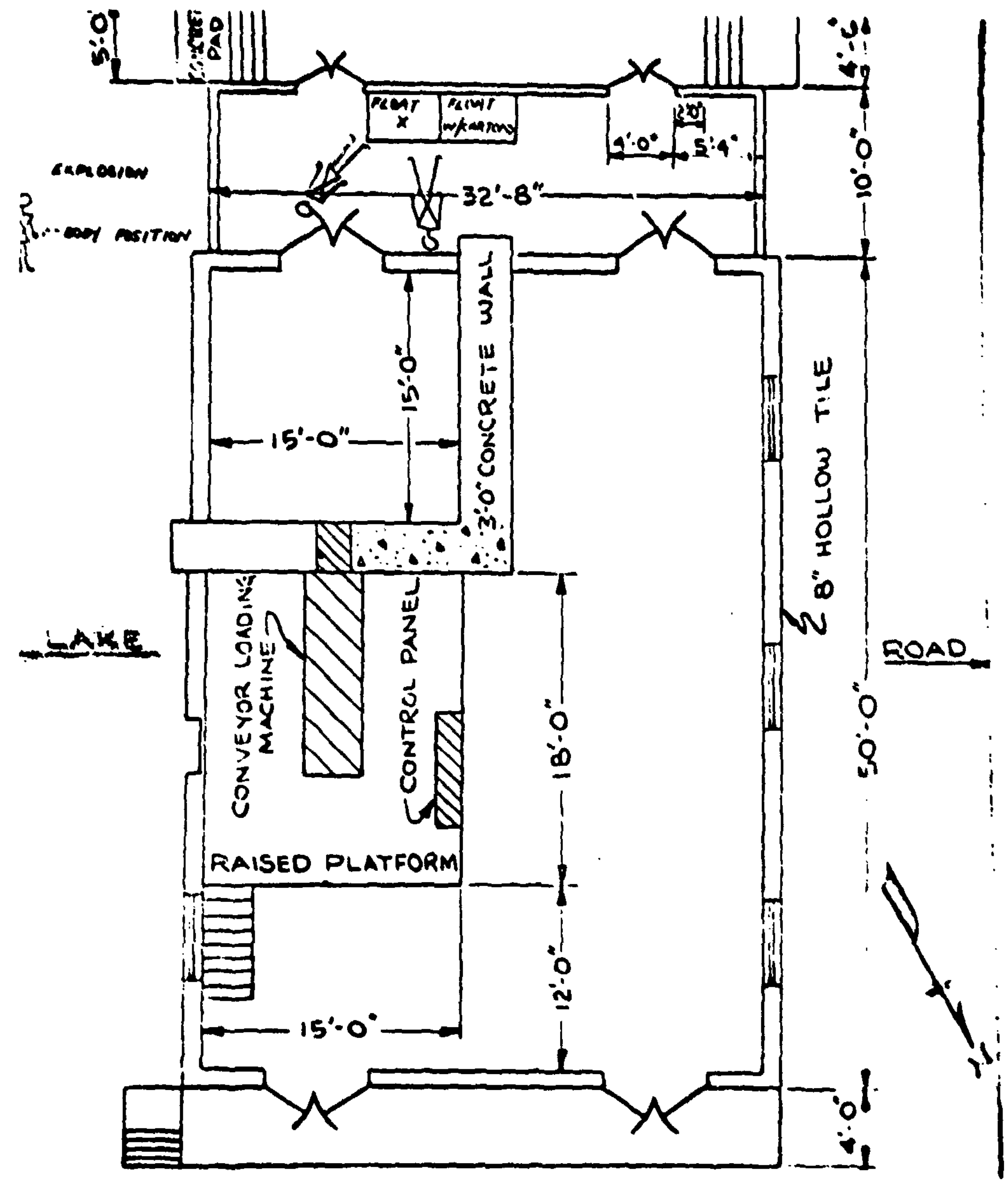

Fig. 14. Building floor plan.

4. Explosives and personnel limits should be reduced to an absolute minimum for safe and efficient operations. Ref para 1601a, AMCR 385-224.

5. Remote control devices and operating shields should be utilized where feasible. Ref paras 2622 and 1001, AMCR 385-224.

V. Subject: Fire in Building Undergoing Modification

Description of Building: The Research and Development Building was a one-story structure, 407 feet long and 98 feet wide at its widest section. It was of concrete and tile construction, with 12" reinforced concrete walls separating the bays. As part of the building modification, metal partitions had been installed and wood furring had been placed on the walls. The floor was made of concrete. The roof deck and covering consisted of wood with asphalt covered metal and transite. A concrete ramp extension, covered with a transite roof, was located at the end of the building in which the fire occurred.

Details of Occurrence: The fire was reported by a civilian guard who first saw the fire while on the front steps of a building one-fourth mile away. The installation fire department responded and started to fight the fire. The intensity of the fire was so great that a decision was made to try to prevent the spread of fire to other parts of the building rather than try to save the portion already involved. The section of the building involved in the fire consisted of three bays and a covered storage ramp at the end. Thirty drums of solvents, which were stored on the ramp, added considerably to the intensity of the fire. The fire was brought under control by the fire department in approximately one hour and completely extinguished four hours and 30 minutes after their arrival on the scene.

Number and Nature of Injuries: None

Causes:

1. Exact Cause: Unknown.

2. Probable Cause: Sparks and/or slag from a welder's cutting torch falling on combustible materials which smoldered and finally ignited.

Remarks:

1. The Research and Development Building was in the process of being modified by converting two end bays, which had been used as an inert storage area, into office facilities.

2. Included in the modification plans was removal of the existing wet fire sprinkler system in that section of the building being modified. On the day of the fire, a welder (using an oxyacetylene torch) had cut and capped the main header of the sprinkler system and cut up the sprinkler pipes into small sections for ease in removal.

3. The fire department was not informed of the sprinkler system shut-off and removal, nor of the oxyacetylene torch cutting operation in the building.

4. The sprinkler system in the adjoining bay to those involved in the fire, activated and helped prevent the spread of the fire to the rest of the building.

5. Openings had been cut in the 12" reinforced concrete walls to enable air conditioning ducts to be installed. Due to the openings, the fire was able to progress from one bay to the other.

6. Welding operations had stopped at 1500 hours. The building was checked on a routine inspection by a civilian between 1645 and 1730 hours. He saw no evidence of fire.

Recommendations:

1. The use of open flame devices should be controlled by written permit. Persons authorized to sign the permit should be independent of the department doing the work and of the department for which the work is being done. Ref par 1606, AMCR 385-224.

2. The fire department should be notified of any proposed changes in sprinkler systems. Its concurrence should be secured before a system is deactivated, altered or removed. Ref para 21, AR 420-90.

3. Local and transmitted water flow alarm facilities should be provided for all automatic sprinkler systems. Ref par 11, AR 420-90.

4. Building construction or modification plans should be submitted to the fire marshal for approval before work proceeds. Ref par 1205, AMCR 385-224.

5. A formal fire inspection system should be initiated in order to perform post-job inspections on job sites where open flame devices have been employed. Ref par 1204, AMCR 385-224.

Fig. 15. Overall view of type of building involved. Damaged sections are to the left of the picture.

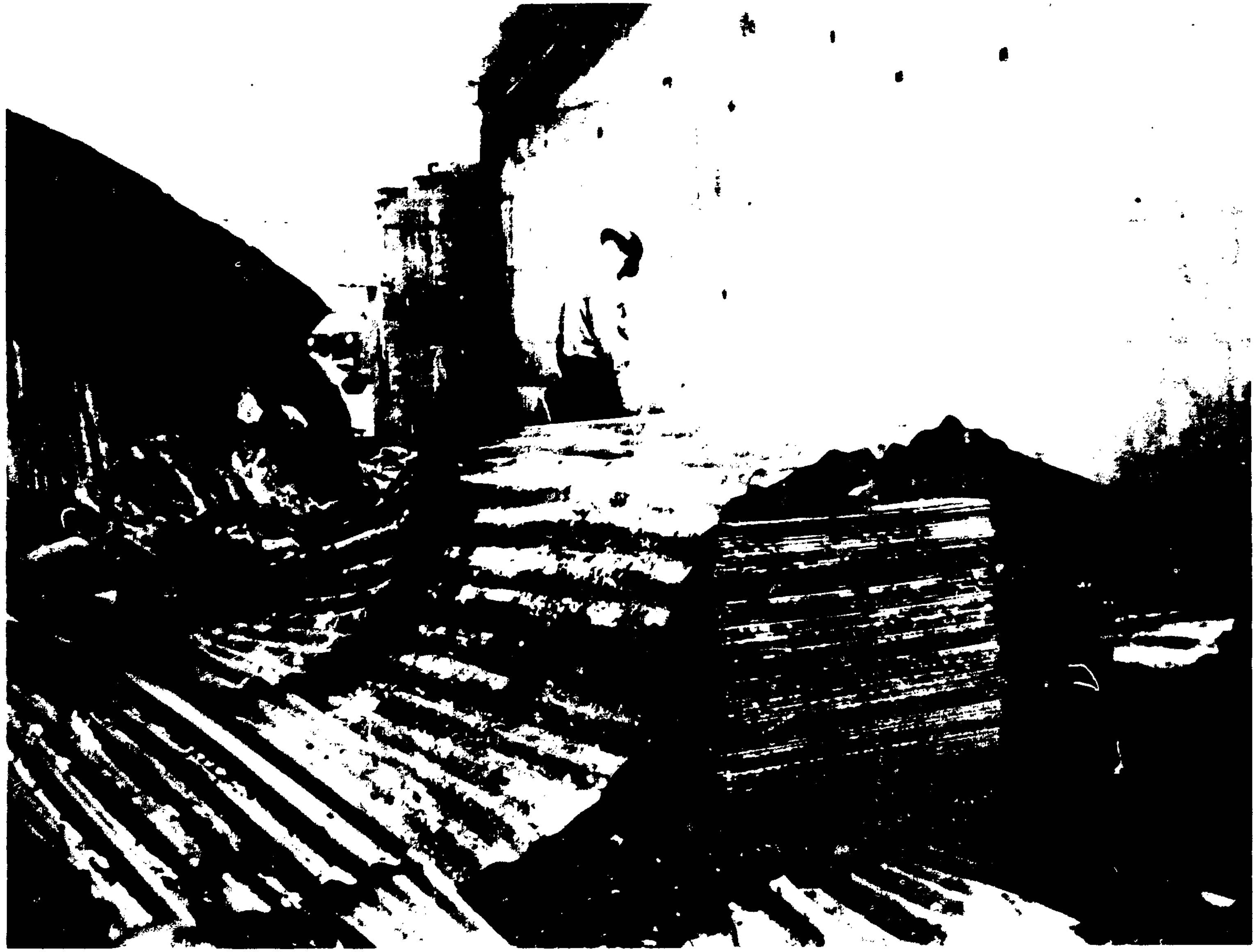

Fig. 16. View shows damage to materiel stored in one of the bays. In this case, the materiel is plywood.

Fig. 17. This scene taken from the end of the building shows type of damage from this angle.

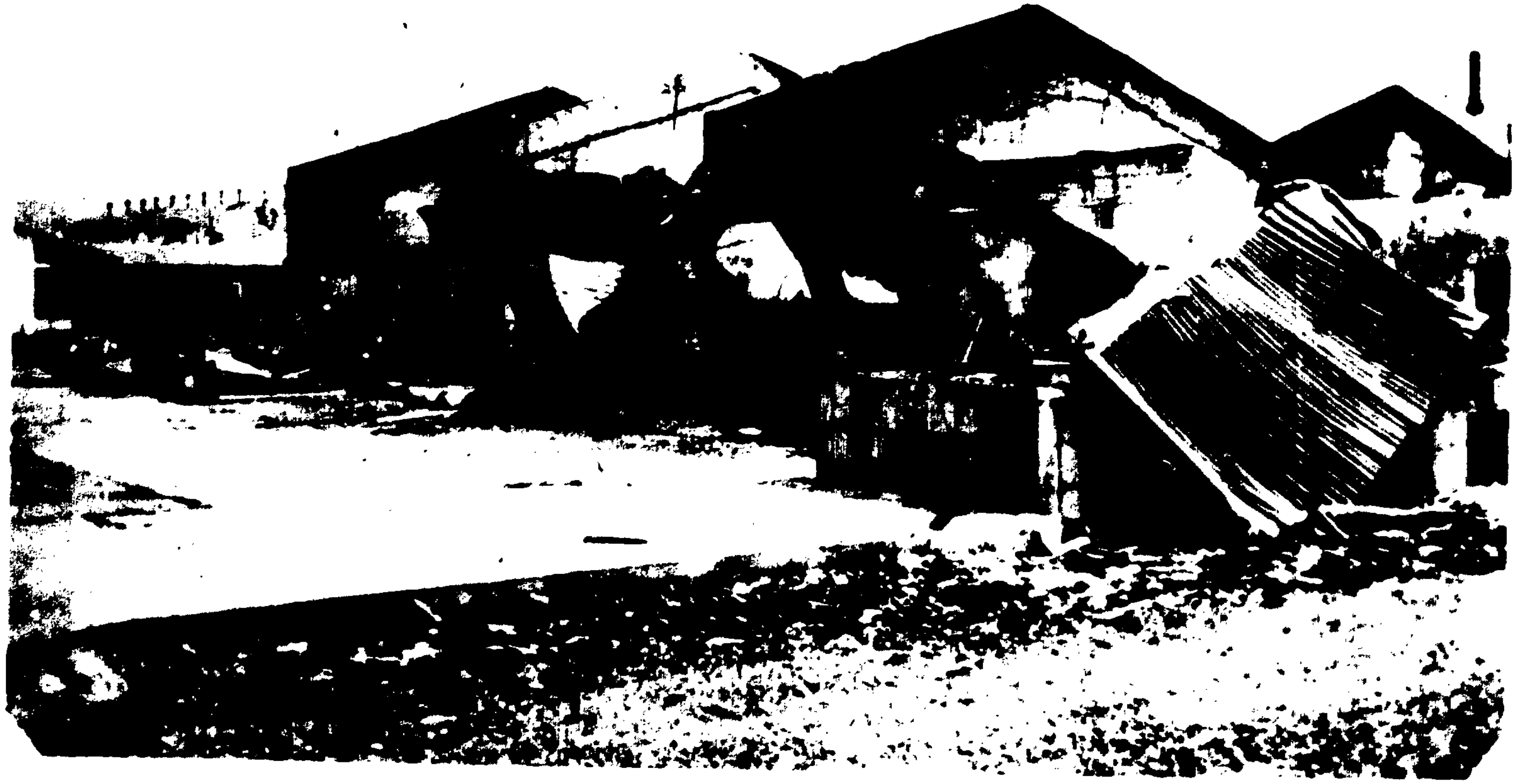

Fig. 18. View of the damaged bays from alongside of the building.

Fig. 19. Close-up view of damage caused by the fire.

VI. Subject: Explosion of Bridge Block during welding

Description of Operation: A bridge block, 9-1/2" high by 11-3/4" diameter weighing 111 pounds, was being repaired by welding.

Details of Occurrence: Prior to repair of the bridge block it was flashed twice to burn off any explosive material. On the face of the block there was a hole into which a metal plug had been previously screwed, welded, and machined. It is believed that a quantity of explosive material (type unknown) was in the hole under the plug. After several applications of extreme heat by the welding torch, the material detonated causing the plug to fly out and strike the welder in the abdominal area.

Number and Nature of Injuries: Fatal - One.

Causes:

1. Direct Cause: Application of heat to the block which was contaminated with explosive.

2. Indirect Causes:

a. Failure of operator to recognize the hazards of application of heat to contaminated item.

b. Failure of supervisory personnel to recognize the hazard of application of heat to contaminated item.

c. Failure of explosives operating personnel to completely decontaminate equipment which had been subjected to explosives prior to releasing equipment.

Recommendations:

1. Employees must be trained in the specific safety rules and regulations for the job to which they are assigned. Ref par 120, AMCR 385-224.

2. Maintenance repair jobs must be closely supervised in order to insure that safe practices and procedures are being followed. Ref par 109, AMCR 385-224.

3. Equipment which has been subjected to explosive contamination should not be released for repair unless it is definitely determined that all such equipment has been given whatever treatment is necessary to insure no explosive material remains. Ref par 301, AMCR 385-224.

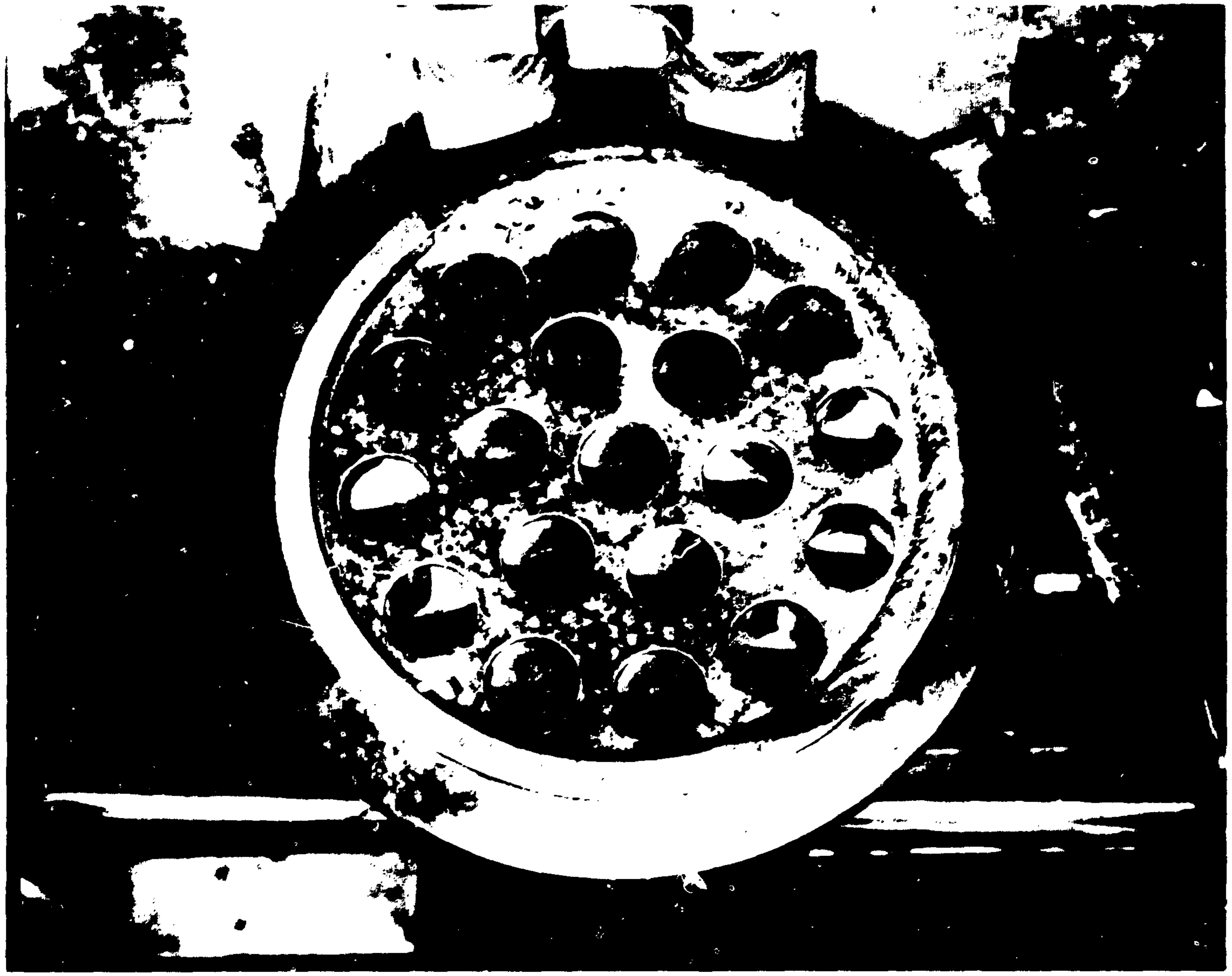

Fig. 20. Front view of bridge plate being welded. Arrow, center, lower, indicates hole from which the threaded metal plug came.

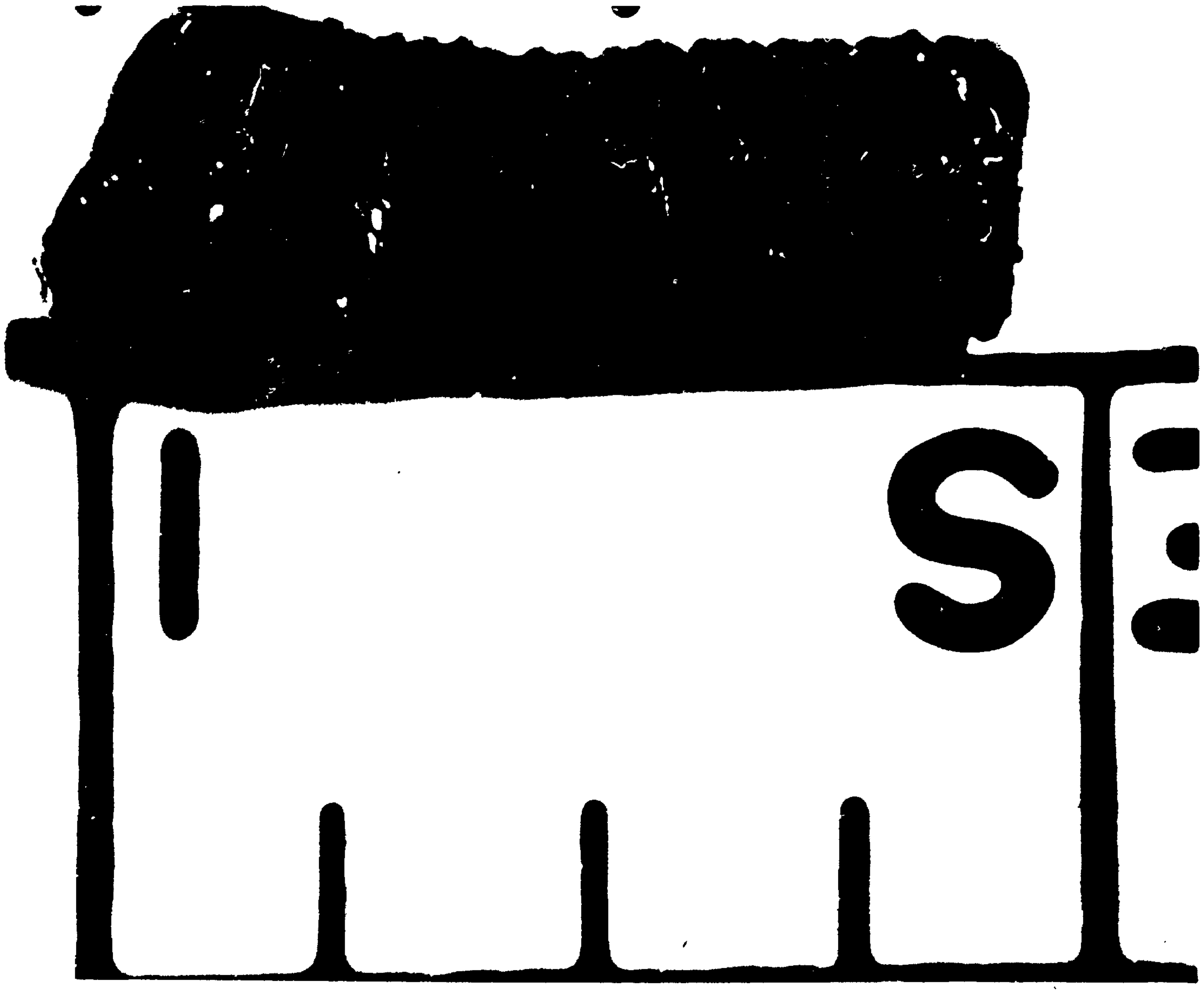

Fig. 21. Lethal plug after being removed from victim.

REPORT OF SPANISH AIR ACCIDENT

by
Maj. D. G. Apostalon, USAF
Chief, Nuclear Safety Branch (DOSDN)
Headquarters, Strategic Air Command

Attendees were briefed on the recent Spanish air incident by Maj. D. G. Apostalon, USAF.

DEVELOPMENT OF A NONLUBRICATED BEARING FOR A VERTICAL MIXER

by
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ABSTRACT

Atlantic Research began to develop a nonlubricated bushing for a Baker-Perkins 16 PVM vertical mixer because vibration in its operation had created a safety hazard. The trouble was traced to the faulty lubrication of the restraining bushing. The maintenance problem on this mixer was twofold: (1) the mixer had to meet production requirements while maintaining a safe, reliable operation; and (2) the mixer had to be repaired, as necessary, while a nonlubricated bushing was being developed. To date, 370,000 pounds of propellant have been manufactured in this vertical mixer with the nonlubricated bushing developed by this effort.

DEVELOPMENT OF A NONLUBRICATED BUSHING FOR A VERTICAL MIXER

In the summer of 1962, Atlantic Research Corporation purchased a Baker-Perkins 16 PVM vertical mixer with a 150-gallon working capacity. Figure 1 shows the mixer with the lower section of the stationary housing dropped, exposing the lower planetary gear housing.

The mixer has an inside and an outside housing. The outside housing is stationary and seals against the bowl. The inside housing, which supports the two mixing blades, rotates in a planetary motion. See Figure 2. The solid blade turns at one-half the speed of the open high-speed blade. The open blade is next to the wall of the mixing bowl; it wipes the side of the bowl both as the blade turns and as the planetary housing rotates.

The stationary housing supports the cast iron restraining bushing which prevents the corner of the open high-speed blade from hitting the bowl. At the time of installation, our maintenance and safety people expressed concern over whether lubricant would be distributed evenly over the restraining bushing, especially over the lower wearing surface, during operation. See Figure 3. Suppose a small cylinder were placed inside a large tube (Figure 4); the best that could be hoped for would be line contact, especially if the lubricant were poorly distributed and the hydrodynamic forces were small. We also thought that the planetary housing might have a pendulum action about its support bearing as shown in Figure 5. If this occurred, the bearing area would be approaching point contact. We realized that there were other units similar to this one in operation; we followed the recommendations for lubrication as stated in the instruction book, and used general purpose grease such as Shell Alvania No. 2.

A fire and an explosion in one of our horizontal units emphasized the need to review the operation and maintenance procedures for all mixers on our plant. After consulting with Baker-Perkins and others in the propellant industry, we decided to use Flurolube (Hooker Chemical GR 362), a nonoxidizing

grease. Flurolube was used between the restraining bushing and the lower planetary housing and on the lower bearings for the mixer blades. At this time, we decided to investigate the feasibility of a nonlubricated bearing.

When the nonoxidizing grease was first used in January 1963, the mixer had approximately forty hours operation; it appeared to be satisfactory. After an additional thirty hours with the nonoxidizing grease, vibration was again experienced. Tests run with inert mixes, while using the Flurolube, established that the amount of grease between the restraining bushing and the lower planetary housing was a factor contributing to vibration when the mixer was under load. The vibration now being experienced while the mixer was under no load was of an intermittent nature, usually occurring during periods of high vacuum. During some of the periods of vibration, it was noted that the oil flow rotameter indicated very little or no oil flow, and sometimes bubbles or foam started to collect in the rotameter.

It was apparent that there was more than one source causing the vibration. A review of the mixer design, lubrication, and lubricants indicated the following areas as potential contributors:

a. Possible lack of oil flowing to the main support bearings of the planetary housing.

(1) The level of the lube oil sump was lower than on other mixers of similar design.

(2) The possibility that the suction of the lube oil pump was not flooded sufficiently to take care of fluctuations in the level of the oil sump.

(3) The size of an oil pump necessary to lubricate the mixer was in doubt.

(4) Air leaks in the system where the piping was under atmospheric pressure.

(5) The correct and proper type of oil for lubrication under the existing operating conditions.

b. The seals being too snug or not properly lubricated.

c. Insufficient or improper lubrication between the planetary housing and the cast iron restraining bushing.

All of the above items that could be corrected were eliminated. This narrowed the field down to the oil pump, the position of the pump suction, and the level of the oil sump. The mixer continued in operation for another eighty hours with intermittent vibration under no-load conditions. The frequency of the occurrences was low, but we were very concerned to determine the cause.

Under the direction of Baker-Perkins, the mixer was inspected and modified as follows:

a. The size of the oil pump was increased from a Brown and Sharp Number 3 to a Number 4.

b. The pump and its suction were lowered.

c. The level of the sump was increased by 1.25 inch.

The cast iron restraining bushing appeared to be in fair condition after a total of 150 hours of operation. The lower planetary housing started to show signs of wear and slight galling. The wear started at a point 15 degrees ahead of the high-speed blade and encompassed an arc of 200 degrees in a direction opposite to planetary housing rotation. The deepest wear marks or grooves in the housing appeared to be caused by the lower edge of the cast iron restraining bushing. Very little grease was found on the lower wearing surface of the bushing. However, large quantities of grease were found in the cavity above the cast iron bushing. (See Figure 3.) These findings strengthened our belief that the planetary housing had a pendulum motion which was forcing the grease out by a wedging action; this action would indicate it was approaching, at best, line contact.

There was an opinion at this time that the clearance between the restraining bushing and the planetary housing should be increased

from 0.018 inch to 0.036 inch on the radius. It was felt that this increase would help to alleviate the wear problem. We had some reservations, but proceeded on this basis. The manufacturer recommended that we go back to a general purpose type of grease to correct the vibration problem. The lower planetary housing was stoned to remove and smooth out the galling and wear grooves. The cast iron restraining bushing was machined to permit the additional clearance. The lubrication procedures were reviewed. We continued to use a nonoxidizing grease in the lower blade bearings but changed back to general purpose lubricant between the lower planetary housing and its restraining bushing.

We wondered whether our operation and experience with this type of mixer was unusual. In talks with others in the propellant industry, we realized that the mix viscosity and the additions sequence contributed to the performance and maintenance of the mixer. Some people had no difficulties; others had operating difficulties similar to our own. The effect of bearing loading on the mixer operation, particularly under varying mix viscosities, is uncertain at best.

An interesting side comment should be made on one of our other installations. A similar mixer was being built at this time; we decided, because of the trouble we were experiencing, to change from the cast iron restraining bushing to some other type of bearing. We agreed with Baker-Perkins to try a lubricated Gatke moulded fabric bearing, a laminated phenolic material. After making approximately 700,000 pounds of material, this bearing has caused little wear on the lower planetary gear housing. On this new unit, the number of lubrication points was increased from two to four, and a flat grease retaining ring, with a turned down outer edge, was added. This design has proven to be very effective. Very little grease has been found in the cavity above the bearing. However, twice grease ran down into the bowl, and the lower planetary gear housing reinforcing gussets have hit the outside stationary housing. A careful check of the blade-to-bowl clearance under load has shown that the mixer maintains this clearance.

The problem appeared to be one of insufficient clearance between the planetary housing and the stationary housing.

The modified older mixer continued to give satisfactory operation for an additional seventy hours; at this point, the high-speed blade began to chatter. Surprisingly, the degree of vertical movement was approaching 0.070 inch. Having experienced operating difficulties in other applications with nonoxidizing grease, we suspected that the Flurolube was probably responsible. The floating lower blade bearings were flushed with a general purpose grease, and the high-speed blade chatter ceased. We were concerned about the condition of the high-speed blade-shaft grease seal, but tests run with inert mixes gave no indication of grease leaking past the seal.

When our difficulties with this mixer began, we decided to monitor the operating temperature of the cast iron restraining bushing. We installed four pencil thermocouples in the restraining bushing which revealed a normal operating temperature between 108°F and 110°F. After another twenty hours of operation, an unusual noise developed when mixing. An increase of 15°F was noted in the four bearing temperatures, and the mixer shut down from an electrical overload. An inspection of the unit indicated that the lower wearing surface of the cast iron restraining bushing had galled and seized the housing. The galling had stalled the mixer; the stalling produced the overload and shut-off. There was enough grease in the cavity (Figure 3) above the bushing and some was on the upper wearing surface. There was no grease on the lower wearing surface of the bushing where it was most needed.

As mentioned earlier, the maintenance department had to return this mixer to safe operation in a minimum of down time. We consulted with Baker-Perkins and decided to attempt installation of a lubricated plastic bearing surface. We bored the cast iron restraining bushing in order to fasten on a 0.25-inch-thick strip of Delrin, a Du Pont crystalline polymerized formaldehyde. This material has outstanding characteristics for stiffness, tensile and compressive strength, and creep resistance. The stiffness gave

us considerable trouble in the installation. It was finally overcome by wedging the Delrin into place and fastening it with flat-head, countersunk cap screws. A 0.75-inch grease groove was cut into the center of the 2.75-inch-wide Delrin strips. About 12 reliefs were made in the lower wearing surface to help the grease work down more effectively. After the Delrin had been installed, a very light finishing cut was made to insure that the Delrin bushing was concentric and to establish a 0.020-inch diametral clearance between the restraining bushing and the stationary housing.

The lower planetary gear housing, after it had seized and was removed, was mounted in a lathe and found to have a number of flat spots from 0.015 to 0.020 inch deep; pieces of cast iron were embedded in it. It was galled and scored very badly. The housing was machined 0.080 inch, but still had deep grooves. These were filled by welding, and the excess was machined until it was blended with the surface. We plated the housing with a hard chrome finish. This left the housing 0.060 inch undersize. The seals were backed with tape until new seals could be purchased.

The main purpose of having the close diametral clearance was to reduce the pendulum motion of the planetary housing. We also felt that the grease would be more effective with a closer clearance, due to the hydrodynamic force effect. At this time we did not definitely associate a close clearance with flat spot elimination; however, we had no flat spots on the housing until we opened the radial clearance from 0.018 inch to 0.036 inch.

The mixer was tested and inspected, using inert mixes, and then checked periodically. From previous experience, we knew that the condition of the lower edge of the cast iron restraining bushing, now covered with Delrin, was critical. The lower planetary gear housing and the restraining bushing always revealed wear at this point. However, the Delrin lined restraining bushing was an exception. After 120 hours of operation, the lower stationary housing was removed. The Delrin showed a wear pattern on 50 per cent of its area. The tool marks from the finishing cut were still visible.

The bottom edge indicated very little wear, and only in spots. The upper and lower wearing surfaces both showed very little wear, except next to the grease groove. However, in the grease groove, where the greatest wear had occurred on the planetary housing, many of the socket-head cap screws were covered with plugs. These consisted of many small, hard, fused-together particles of Delrin. The grease was loaded with these particles. We felt this indicated that local hot spots had developed or that the grease had approached 350°F, the melting point of Delrin. The worn Delrin areas were not worn in a normal manner; instead, it appeared that something hot had melted away very thin Delrin layers. We concluded that the hot grease had caused the thin surface layers of Delrin to melt and form droplets. These, in turn, formed particles which were caught in the cavities of the countersunk cap screws and fused. The others remained in the grease and acted as an abrasive. The worn or melted area was only slightly deeper than that which was necessary to remove the tool marks. Figure 6 shows the Delrin bearing just before it had been replaced. The picture shows two of the cap screws partially covered by the fused particles; other screw cavities shown had been cleaned before the picture was taken.

The planetary housing was worn directly opposite and on each side of the grease groove for a distance of 0.312 inch from the edge of the groove. This wear area formed a uniform band 1.37 inches wide around the housing circumference to a depth of 0.020 inch. The profile of the worn area, shown in Figure 7, formed an irregular, shallow V. There were many small horizontal grooves or ridges. There was no noticeable wear in the area 0.687 inch from the edge of the worn area, top or bottom, where the housing was still supposed to be in contact with the Delrin bearing surface. The housing had no flat spots.

At first we could not explain this pattern of wear; then we realized that the reduced diametral clearance had eliminated the pendulum motion and that the grease was restraining the housing. The hydrodynamic pressure of the grease was supporting the planetary housing. We found grease on the

lower wearing surface and, to a greater degree, on the upper wearing surface. Most of the end leakage was in the cavity above the restraining bushing. We had used more grease more often during the Delrin bearing operation; the amount of grease found in the cavity was not unusual. In short, the grease was staying where it was needed.

As a result of the Delrin melting and the abrasive action of the melted particles, we decided to replace the Delrin with a nonlubricated bearing material. As mentioned previously, we had established a program to investigate the elimination of the lubricated bearing. We chose a filled Teflon, Rulon A, made by the Dixon Corporation, Bristol, Rhode Island. Du Pont TFE Teflon has a very low coefficient of friction, but the unfilled TFE has limited physical properties. However, in combinations with various fillers, such as fibrous glass or molybdemum disulfide, the PV value can be increased from 1000 to 20,000 without adverse effect on other properties. The Dixon Corporation claims that Rulon A has a 1000-fold increase in wear resistance over unfilled TFE, in addition to lower deformation under load, greater stiffness, and higher compressive strength.

The planetary housing had a groove slightly larger than the area of the grease groove in the old cast iron bearing profile. We decided not to repair or restore the housing; we did not fully appreciate how good a bearing material we had with Rulon A at this time. Originally we intended to put the bearing up with no radial clearance and to let it work out, establishing its own close clearance. This is the procedure we would have used with unfilled TFE. We did not know what to expect; but regardless of the results, we would have an opportunity to observe the behavior of Rulon. The restraining bushing with its Rulon liner was installed with no clearance. The seals were not installed in the mixer, and the area around the blades was barricaded. The end product, after a few modifications, was an excellent prony brake. The mixer ran under no load except that of the bearing. The Rulon coefficient of expansion is relatively low, 4.2×10^{-5} per degree F, between +400°F to +78°F; but in this case, it was too much. The Rulon sagged and flowed due to the generated heat; in

some areas, it was fused to the housing, which approached a temperature of 600°F, plus. Temperature was determined by the color change of the 304 stainless steel exposed in the worn groove, and by a pyrometer. The results of this test proved:

a. The method for fastening the Rulon with 5/16-inch flat-head countersunk cap screws and Locktite A was very effective.

b. The thermocouples, even though they were against the Rulon, lagged the temperature increase. They only reached 145°F.

Another Rulon A bearing strip tape was installed with approximately 0.030-inch radial clearance. Figure 8 shows this bearing before the stationary housing was raised. The mixer was checked with high viscosity inert mixes. The mixer vibrated when first placed under low-speed load for about two minutes. After this period, no further vibration would be noted until the surface on the planetary housing was disturbed. For example, when lowering the stationary housing, the Dow-Corning Number 20 Silicone grease used to lubricate the seals would smear and would have to be cleaned off with acetone. The mixer would then vibrate again when first put under load for a few minutes. We concluded that the Rulon transfers a very light Teflon coating on the planetary housing. Until this transfer is accomplished, the vibration will persist.

The speeds of the planetary housing are as follows:

Gear	RPM	Surface Velocity
Low	6.6	73 ft/min
Second	9.9	109 ft/min
Third	13.4	147 ft/min

During a normal mix cycle, the low speed would operate for 50 per cent of the time; second and third, about 25 per cent each. When the vibrations began, due to poor restraining bushing lubrication or, in the case of the Rulon, under initial load, we discovered that vibration frequency increased in direct

proportion to the rpm. The low speeds of the housing gave us considerable leeway, in the area of pressure, when reviewing the PV values of various materials.

The true pressure against the restraining bearing has always been open to question. Baker-Perkins calculated it to be between 250 to 300 psi by using the projected area of the bearing. We believed that the pressure was somewhat greater than this because the bearing approaches line contact. The Delrin liner, on which the grease supported the housing, is an exception. The ASTM method of measuring plastics under load is as follows: 24 hours under a compressive stress of 1000 psi and temperature of 200°F. Recovery for 24 hours. Deformation for Rulon A is 2.7 per cent; for Delrin, 0.5 per cent. The crude tests that we have conducted indicate that Rulon A would not take any significant permanent deformation when load was applied and quickly removed, until the compressive stress exceeded 100 psi. If the compressive stress stayed below 400 psi and was of short duration, the permanent deformation would be, at most, 0.8 per cent after a recovery period of 24 hours. If, however, 400 psi were applied, immediately after the short duration load, the deformation would be as high as 5.8 per cent.

Figure 9 is a profile of the surface of the lower planetary gear housing after 64 hours of operation with the Rulon tape. The polishing of the bottom of the 0.015- to 0.020-inch-deep groove caused by the Delrin liner puzzled us. No visible distortion or other significant change took place on the Rulon bearing. We could only conclude that the Rulon was deforming under load then recovering. When the Rulon A tape was installed; it measured approximately 0.258 inch in thickness. After 500 hours of operation, it measured 0.255 to 0.257 inch. If the reduction of thickness resulted from deformation alone, the greatest compressive stress would be 400 psi or smaller. The amount of bearing contact area is still unknown. We have estimated this to be about 34 square inches.

The wear characteristics of Rulon, chrome, and 304 stainless steel turned out to be very interesting. The lower edge of the restraining bushing

and thr housing were checked weekly. The mixer was checked after running inert mixes, and again after 50,000 pounds of propellant was produced. Very little wear was noted. See Figure 9. We have just discussed how this wear pattern started to change the small ridges caused by the Delrin liner. The relatively undisturbed chrome surface areas were starting to show wear; slight signs that flat spots were forming on the housing were visible. A definite pattern was discovered at the inspection after 187 hours of operation. See Figure 10. The chrome surface had started to wear very rapidly, and the bottom of the groove was almost polished smooth. The Rulon was wearing a very pronounced area of the planetary housing; the Rulon itself showed no appreciable wear. The wear rate on the hard chrome was determined to be 0.001 inch per 10,000 pounds of propellant; on the 304 stainless steel, it was 0.001 inch per 100,000 pounds of propellant. The Dixon Corporation has shown the same coefficient of friction, 0.15, for Rulon A against both chrome-plated steel and stainless steel. There definitely appear to be other factors which need consideration when trying to explain wear rate; possibilities include lubricity of the surface or the coating transfer by the Rulon A.

At this point, the planetary housing shows many more flat spots. The deepest (0.020 inch) is located 70 degrees ahead of the high-speed blade. The pattern could not be correlated with the wear pattern when the mixer was disassembled after the initial 150 hours of operation. At this point, we realized that the clearance between the planetary housing and the restraining bushing directly affected the growth of flat spots on the housing. The radial clearance had increased from 0.030 inch to 0.042 inch during the first 187 hours of operation. This increase was caused by the removal of the hard chrome plate. During the remaining period of operation with the Rulon A bearing, there was practically no significant increase in the average clearance because the chrome was gone and the 304 stainless steel has a lower wear rate. However, the flat spots continued to grow and increase.

To maintain the radial clearance, we could shim behind the Rulon, but we could not decrease the Rulon A bearing diameter below that which would

pass over the larger diameter of the lower unworn portion of the housing. See Figure 10. Therefore, we considered a removable step type of wear ring, as shown in Figure 11. A stepped wearing surface on the housing would permit very close control of the radial clearance. This control would minimize flat spot development.

Baker-Perkins collaborated with us on a preliminary design for a new wear ring. We were to investigate the possibility of a moulded, filled Teflon bearing, and Baker-Perkins would provide a design for a removable wear ring of a step type.

Early investigation showed that initial cost for tooling and machining prohibited use of a moulded bearing. The tape strip bearing material was the most economical. Dixon Corporation suggested that a tape liner be used with an outer sleeve so that the liner could turn and take care of the expansion by a bias cut. However, the Rulon A tape being used was not permitted to turn, and the final decision was to retain the existing method of fastening the Rulon A tape.

We discussed our chrome-plate wear rate findings with the Dixon Corporation. Dixon said that chrome-plate wear rates differ for steels plated by different platers. They suggested Dixon Teflon Grease Number 129. When this grease was used on the Rulon A bearing, the vibration of the mixer under load could not be dampened. If more grease had been available, the vibration could probably have been eliminated. However, we felt that this was a step backward, so this line of attack was dropped.

The planetary housing now had flat spots which made us concerned about the safe operation of the mixer. We decided to repair the worn area by building up with weld and peening while hot. Welding would be done with a 3/32-inch rod and a short arc. It was to be done in 3-inch square areas, 180 degrees apart around the housing. A wear ring would then be shrunk on the housing. Unfortunately, the contracting machine shop did not have the welding capability to do a proper job. While checking their work, we found the alignment

of the lower-blade bearing bores to be unacceptable in relation to the upper planetary housing. However, the most important observation was that the housing was dimensionally unstable. Small changes in temperature, approximately 30°F, would cause the housing to shift 0.030 to 0.040 inch due to the relatively small thermal stresses coinciding with the high residual peaks. A new housing with a removable wear ring is on order. In the design of the wear ring, Baker-Perkins recommended that the diametral clearance be 0.040 inch.

Figure 12 is a picture of the planetary housing after 500 hours of operation. Figure 13 shows the Rulon A tape bearing liner with 500 hours operation; it is in practically the same condition as when originally installed.

In summary, I would like to say that we feel that the interface between the Rulon A and the 304 stainless steel wearing surface that we have used has given very satisfactory operation. The Rulon A bearing surface has eliminated one possibility for contamination of the propellant with grease.

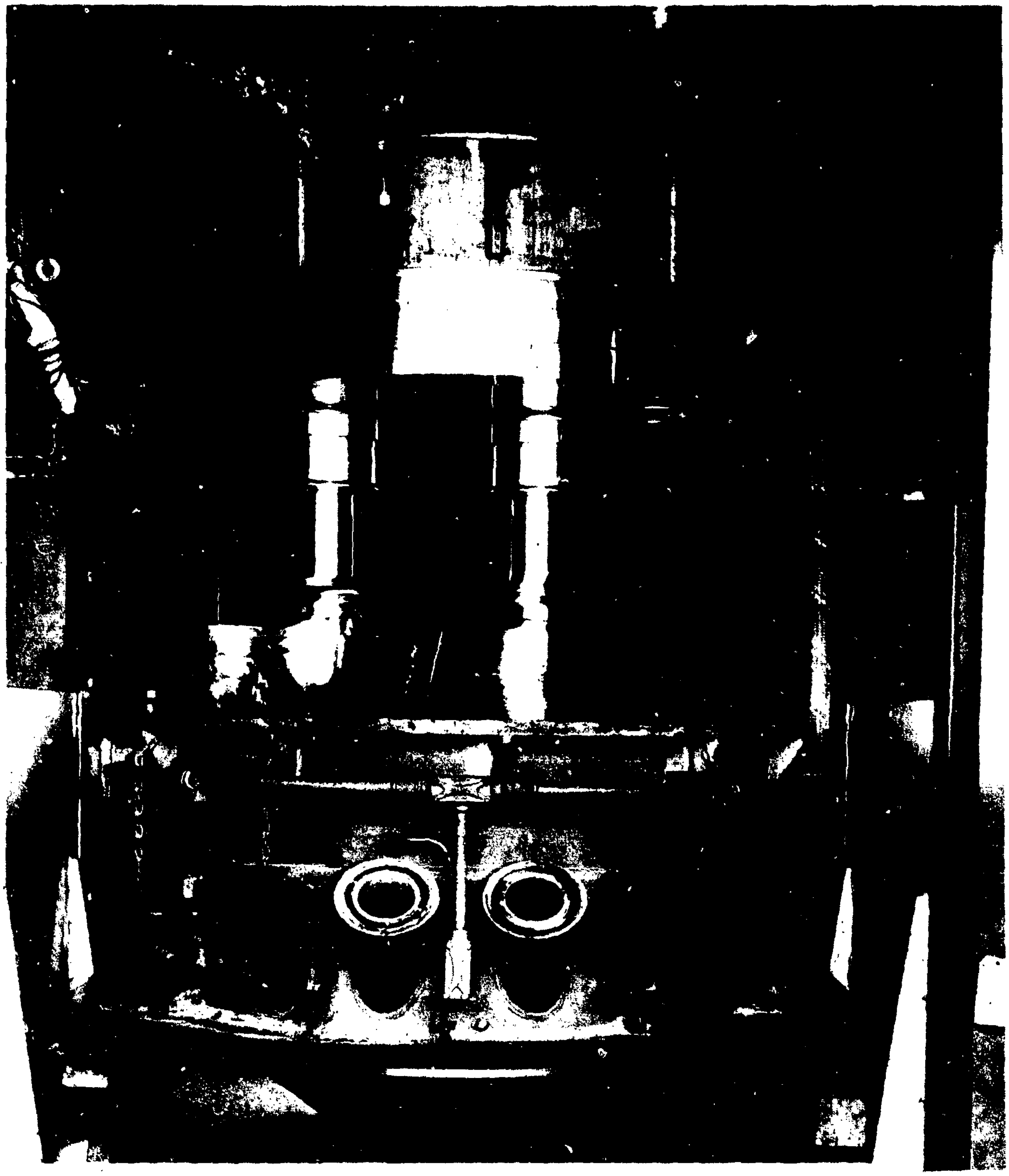

FIGURE 1.

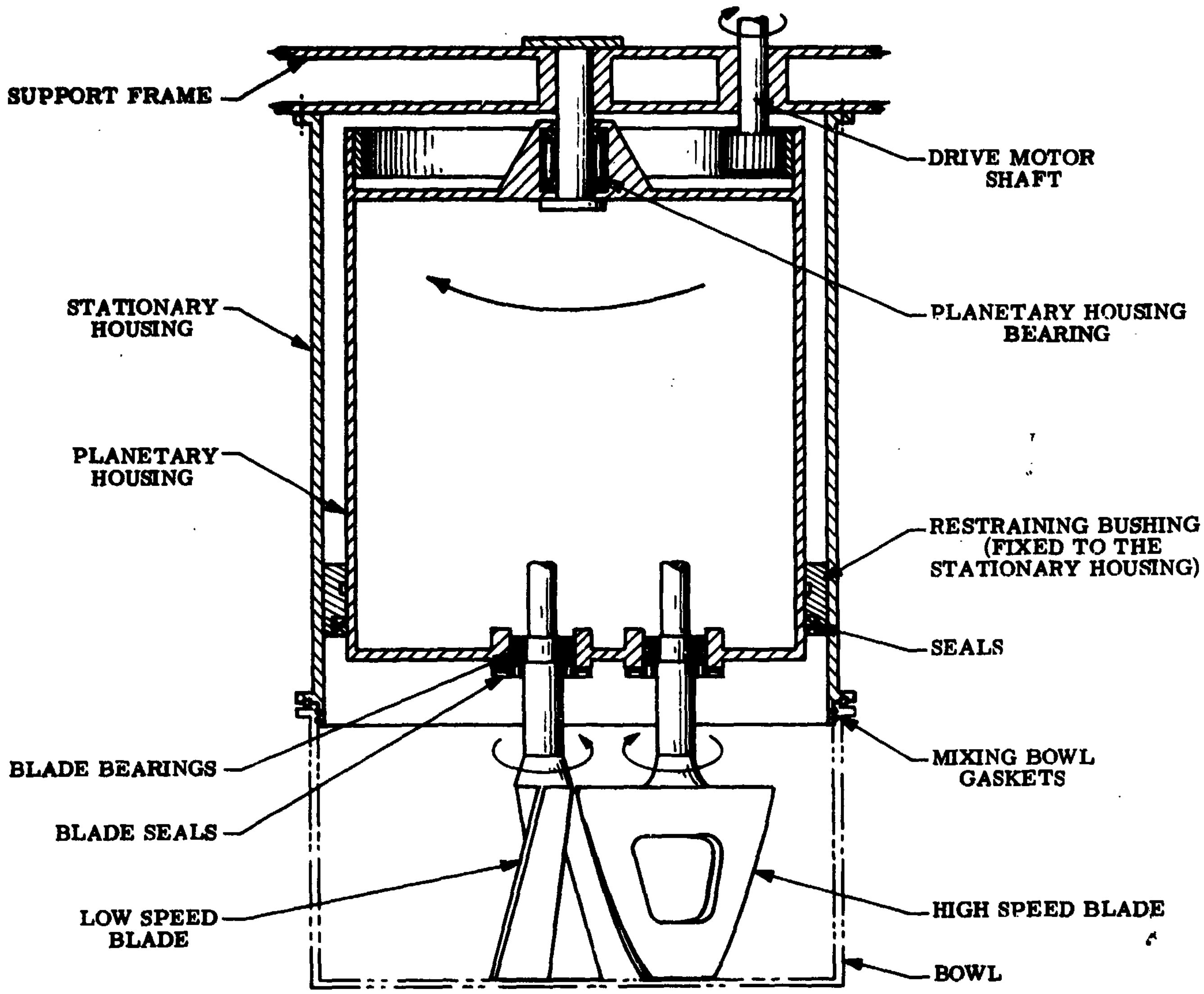
SUPPORT FRAME
DRIVE MOTOR SHAFT
STATIONARY HOUSING
PLANETARY HOUSING BEARING
PLANETARY HOUSING
RESTRAINING BUSHING (FIXED TO THE STATIONARY HOUSING)
SEALS
BLADE BEARINGS
MIXING BOWL GASKETS
BLADE SEALS
LOW SPEED BLADE
HIGH SPEED BLADE
BOWL

FIGURE 2.

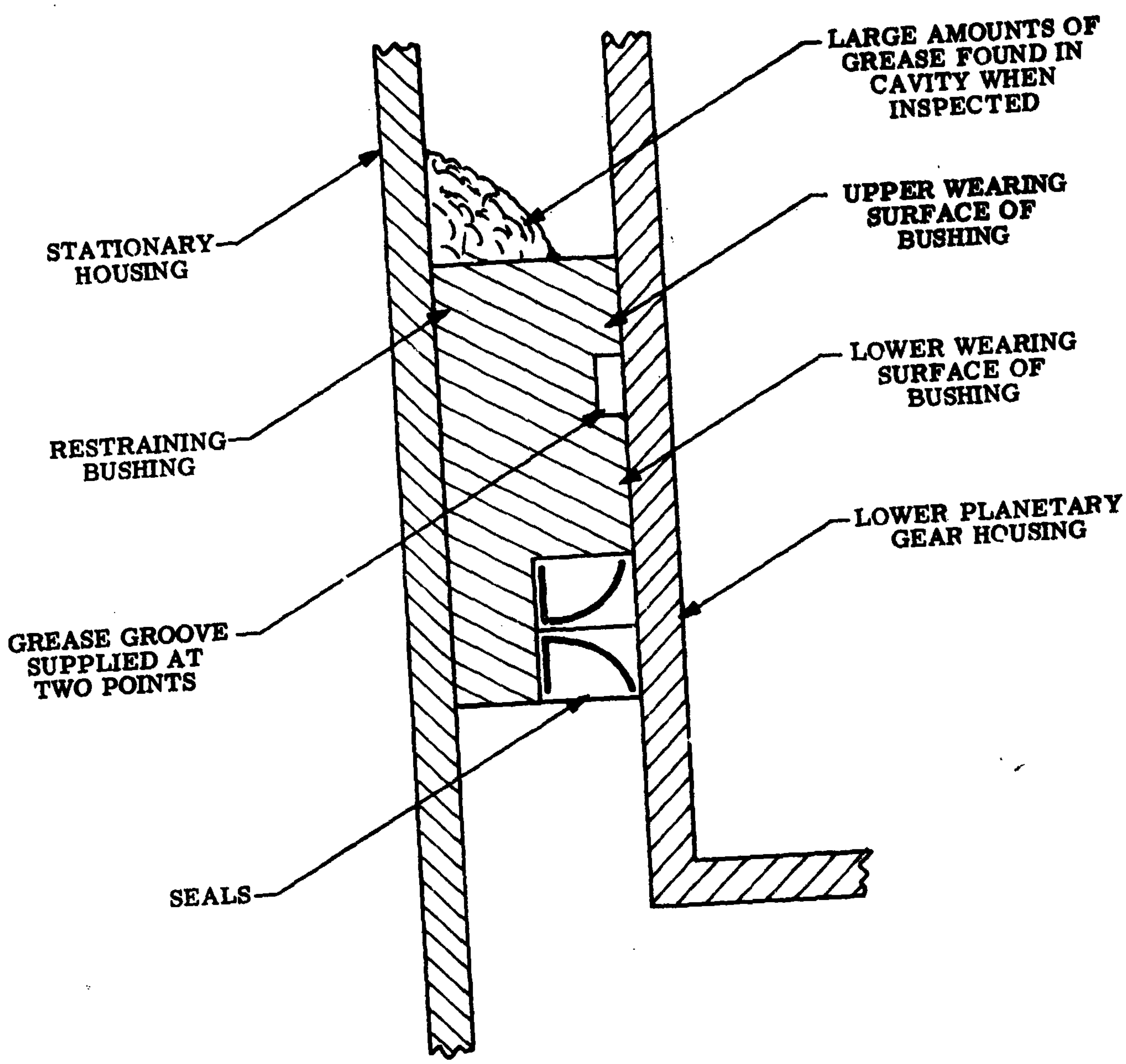
LARGE AMOUNTS OF GREASE FOUND IN CAVITY WHEN INSPECTED
STATIONARY HOUSING
UPPER WEARING SURFACE OF BUSHING
LOWER WEARING SURFACE OF BUSHING
RESTRAINING BUSHING
LOWER PLANETARY GEAR HOUSING
GREASE GROOVE SUPPLIED AT TWO POINTS
SEALS

FIGURE 3.

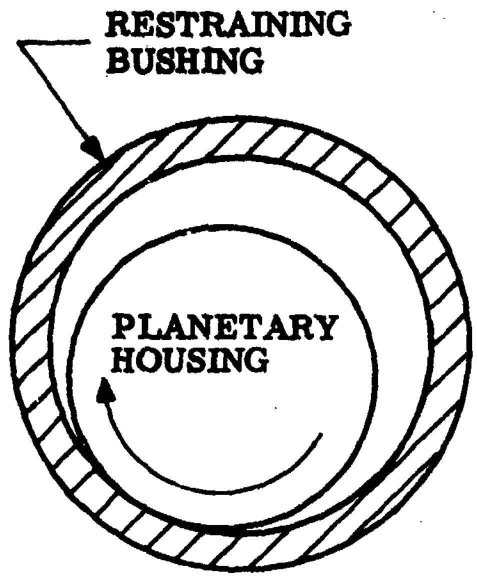

FIGURE 4. TOP VIEW ILLUSTRATION OF LINE CONTACT.

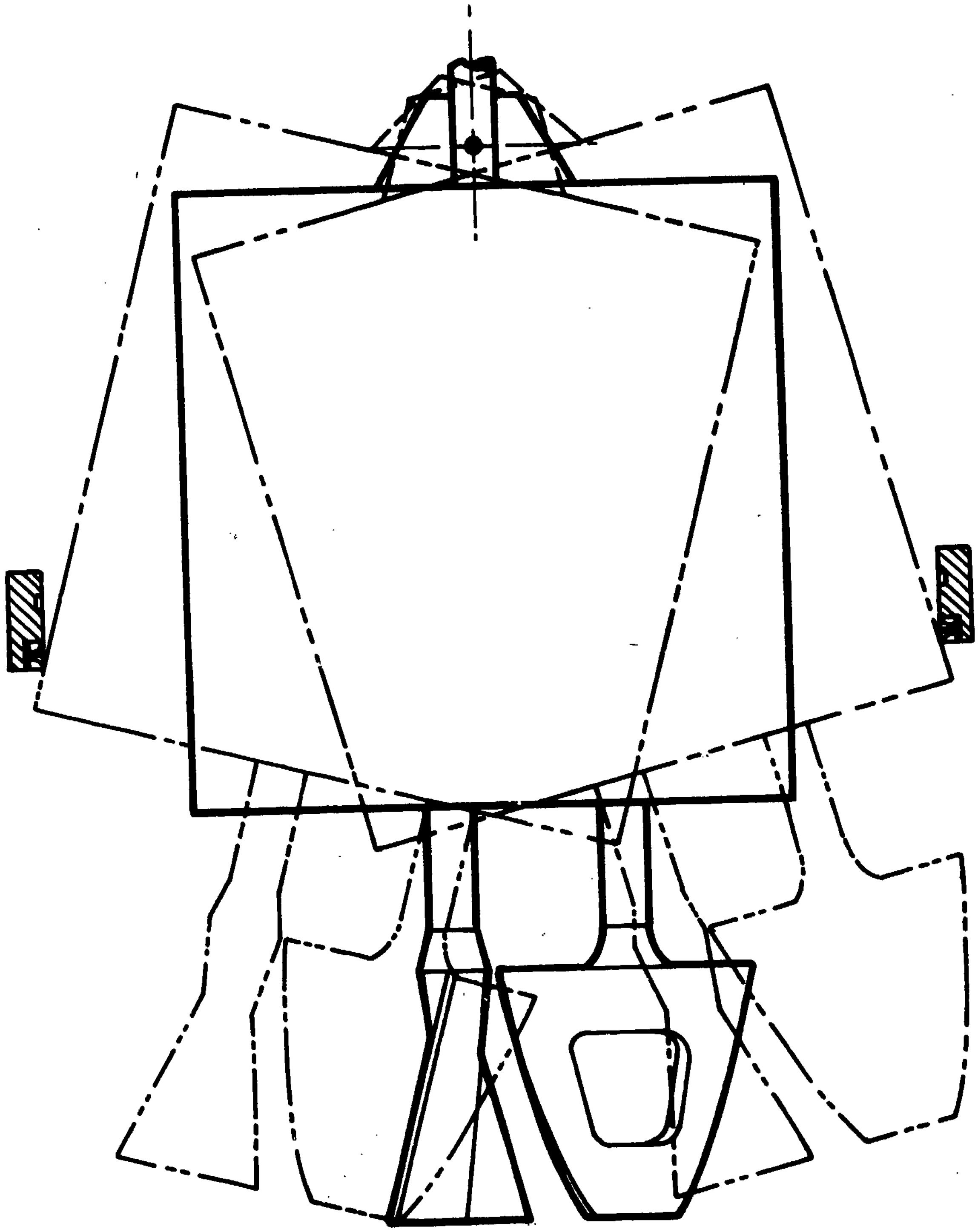

FIGURE 5.

FIGURE 6. DELRIN LINER AFTER 120 HOURS.

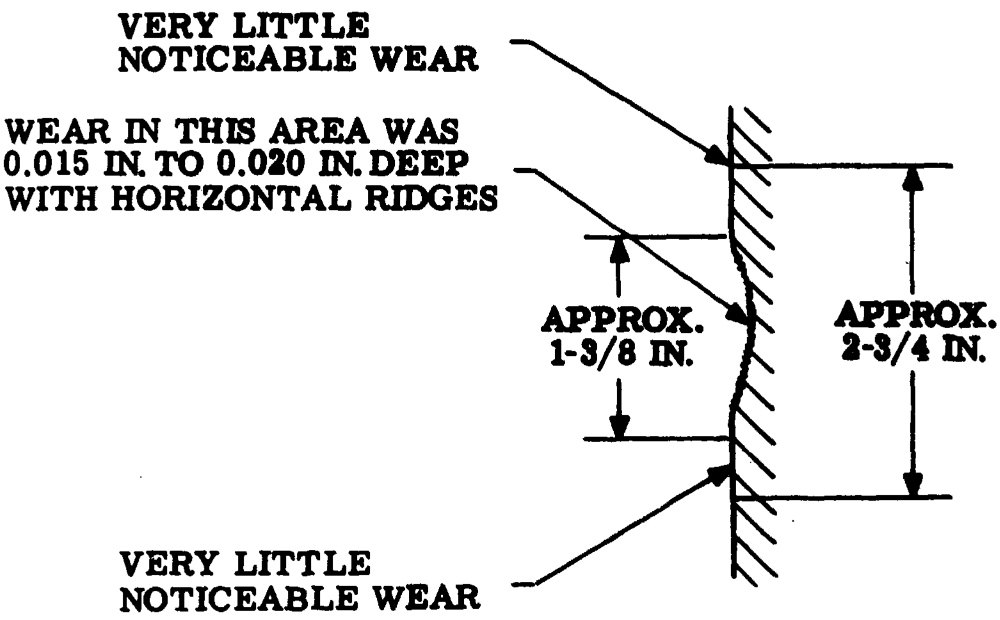

FIGURE 7. SURFACE PROFILE OF LOWER PLANETARY GEAR HOUSING AFTER 120 HOURS OF OPERATION WITH THE DELRIN LINER.

FIGURE 8. NEW RULON LINER, 3-1-64.

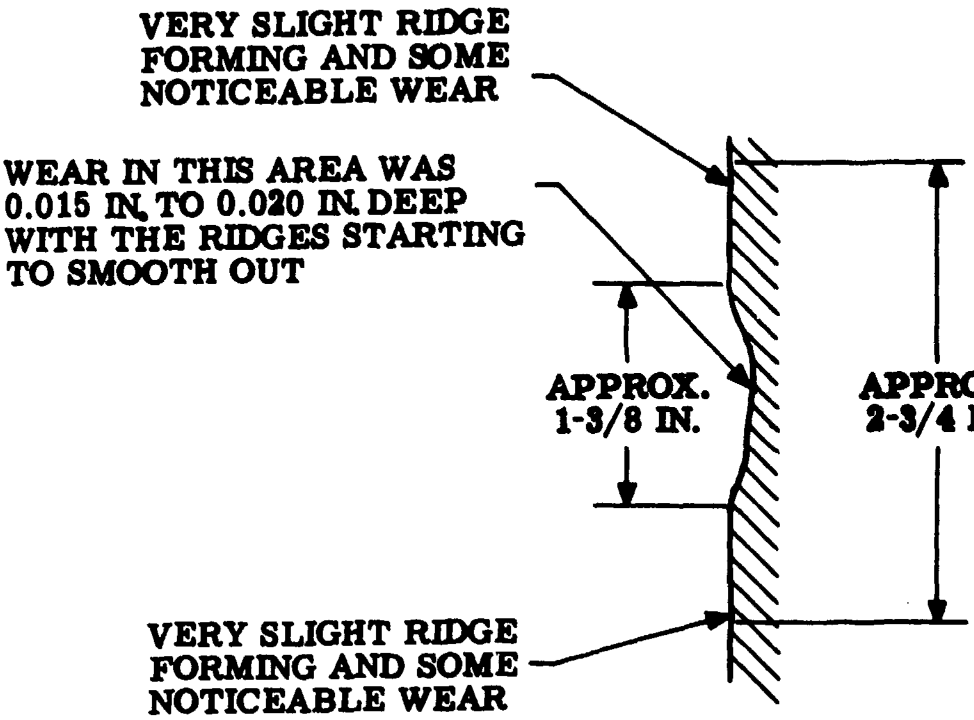

FIGURE 9. SURFACE PROFILE OF LOWER PLANETARY GEAR HOUSING AFTER 64 HOURS OF OPERATION WITH THE "RULON A" TAPE LINER.

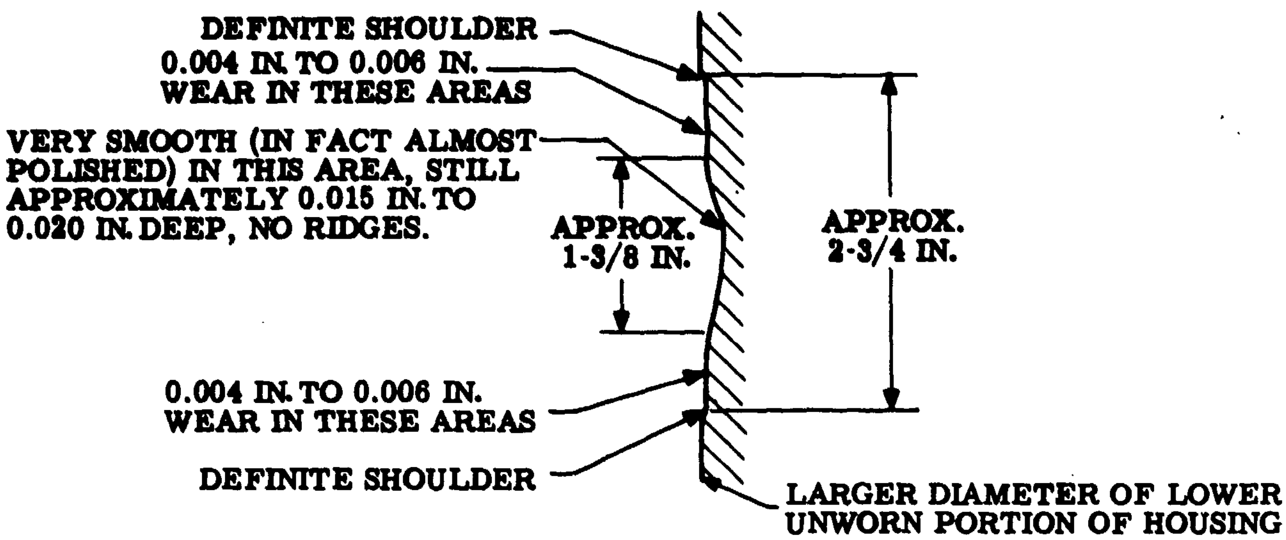

FIGURE 10. SURFACE PROFILE OF LOWER PLANETARY GEAR HOUSING AFTER 187 HOURS OF OPERATION WITH THE "RULON A" TAPE LINER.

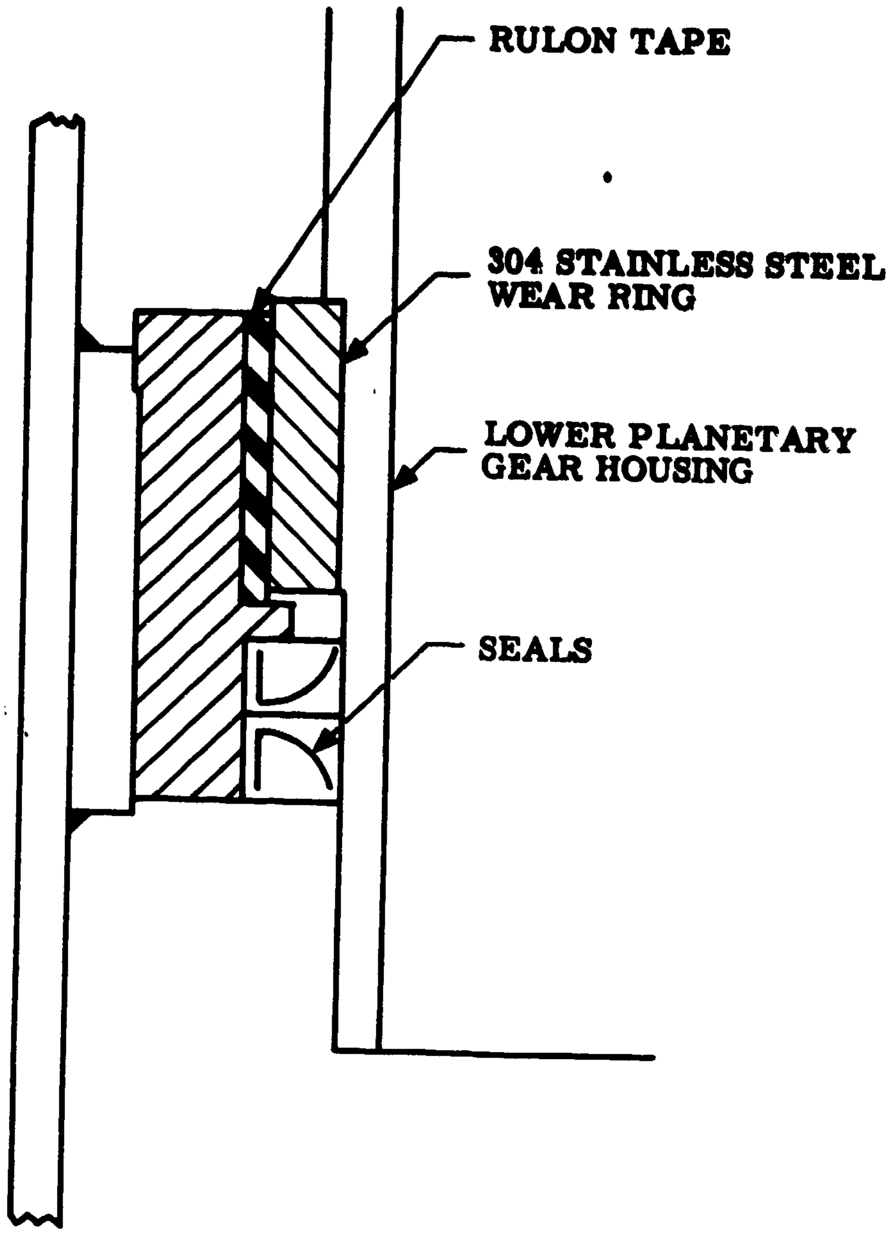
RULON TAPE
304 STAINLESS STEEL
WEAR RING
LOWER PLANETARY
GEAR HOUSING
SEALS

FIGURE 11.

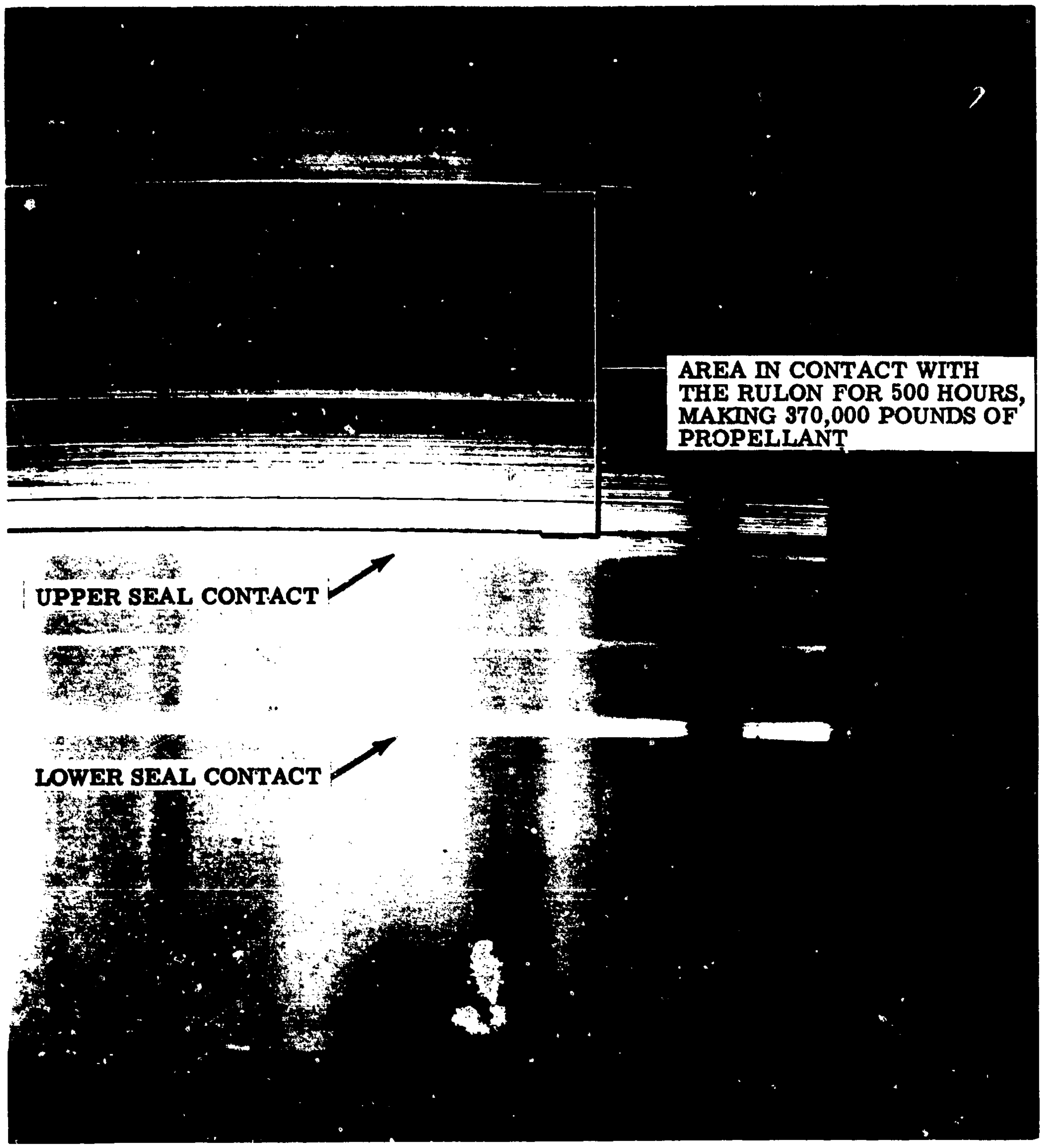

FIGURE 12. LOWER PLANETARY GEAR HOUSING AS IT APPEARED BEFORE BEING SENT OUT FOR REPAIRS.

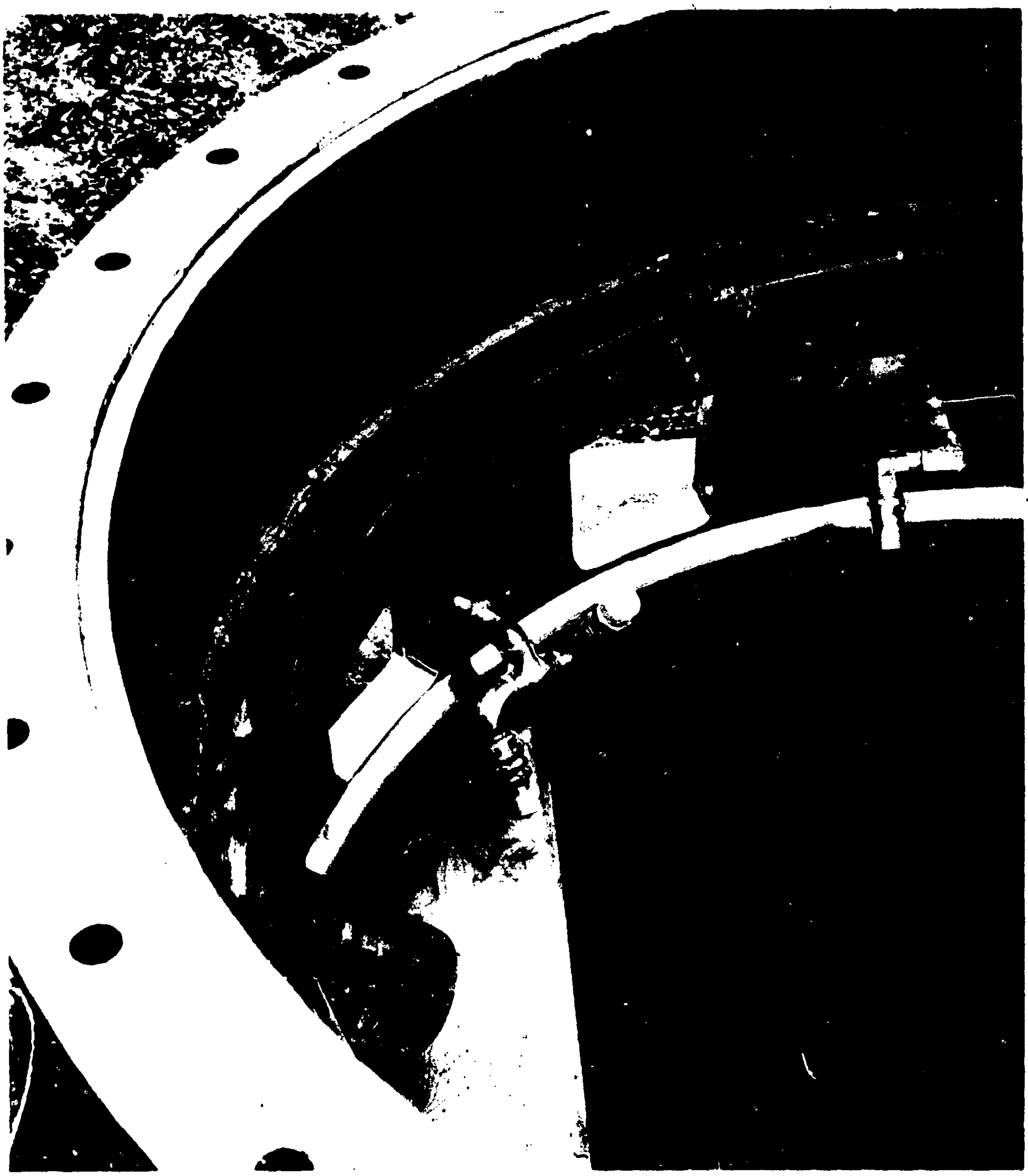

FIGURE 13. RULON BEARING TAPE AFTER 500 HOURS, MAKING 370,000 POUNDS OF PROPELLANT.

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ECONOMIC UNDERGROUND STORAGE OF SMALL LOTS OF HAZARDOUS MATERIALS

by

T. H. Pratt
Rohm and Haas Company
Redstone Research Laboratories
Huntsville, Alabama

ABSTRACT

Pipe fields consisting of suitably spaced dry wells have been designed and proof-tested for safe storage of potentially hazardous materials. Tests with 5-lbm-charges of Composition C-4 explosive have demonstrated that 6-ft-deep wells on 10-ft centers restrict earth effects to camouflet formation. Similarly, high-order detonations of 25 lbm of explosive or propellant in 12-ft-deep holes 10 inches in diameter form camouflets having diameters no larger than 8 feet. Underground storage in a properly laid out pipe field not only precludes sympathetic reaction between adjacent sites but preserves the physical integrity of all sites neighboring the site of an explosive malfunction.

ECONOMIC UNDERGROUND STORAGE OF SMALL LOTS OF HAZARDOUS MATERIALS

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Introduction

The concept of a pipe field for the storage of potentially hazardous samples is a straightforward one; samples are stored in properly spaced pipes extending underground such that inadvertent explosions will be contained by the earth and not propagate to adjacent locations. Pipe-field storage has several advantages over ordinary above-ground-magazine storage of explosive samples, especially when the experimental nature of the compounds or an extreme storage environment makes their stability doubtful and spontaneous explosion correspondingly more likely. Personnel handling a sample are exposed to the hazard of only a single sample, both from the standpoint of original initiation and from that of propagation to adjacent explosives. The first cost of the pipe field is ordinarily lower than comparable surface storage, and cost of repair after an incident would always be less. For a given total quantity of explosive the subdivision used in the pipe field results in more favorable quantity—distance requirements and thus more convenient location with respect to the operating buildings served. Furthermore, in use of pipe-field storage for surveillance studies, if an incident occurs, the malfunctioning sample is easily identified and the degree of reaction can be weighed.

Criteria

Proof tests have been performed with 5-lbm and 25-lbm charges of Composition C-4 to demonstrate that below-grade storage is acceptable from the standpoint of safety. The criteria of acceptability of the proof tests were as follows: (a) the detonation of high explosive would form a camouflet rather than an ordinary crater, (b) no high-velocity ejecta would be laterally thrown toward the area above an adjacent pipe, (c) the resulting fireball emanating from the test pipe would not reach the area above an adjacent pipe, (d) the area of ground upheaval would not extend to the mouth of an adjacent pipe.

Test Procedures and Results

5-lbm Tests - For lay-out of the 5-lbm capacity facility the pipe depth and spacing was determined by an extrapolation of earlier data (1) obtained for the design of a pipe field to contain 1-lbm samples.

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(1) J. P. Swed, "Facilities and Equipment for Remote Operations in Research and Experimental Production of Sensitive Propellant Chemicals", Minutes of the Fourth Explosive Safety Seminar on High-Energy Solid Propellants, Armed Services Explosives Safety Board, HESP Aug. 1962 (Confidential), p. 123 (unclassified).

The test facility was constructed with 10-in. Schedule 40 poly(vinyl chloride) pipe 73 inches long inserted into the ground on 10-ft centers to a depth of 6 feet, leaving 1 inch above ground.

The test charges were right-circular cylinders of Composition C-4, 4 inches in diameter, 5.5 inches long, packed to a density of 1.59 gm/cc. These charges were placed on the bottom of the pipe and axially initiated with an Engineers' Special (J2) blasting cap.

Each event was photographed with high-speed motion picture cameras; still photographs were also made before and after each event. On one test a kraft-paper—plywood witness screen (Fig. 1) was used to determine if high-velocity ejecta were thrown toward the area above an adjacent pipe. A line of 18-in. stakes on 3-ft centers was placed 2 feet in front of the pipe to serve as reference marks on the resulting photographs (Fig. 2).

In all three 5-lbm tests camouflets were formed rather than craters. These camouflets were all 3 feet in diameter; assuming them to be spherical, the centers were $6\frac{1}{2}$ feet below grade. Loose earth covered the bottoms of the cavities to depths of 1 foot. The diameters of the upper portions of the holes were 16 inches.

The dimensions of the fireball and earth upheaval were obtained from the motion pictures. The gaseous products escaped through the pipe and formed a fireball $13\frac{1}{2}$ feet along a horizontal diameter above the test site. The fireball rose with time and finally dissipated into a cloud of smoke. The surface of the earth was heaved upward around the

pipe to a diameter of $11\frac{1}{2}$ feet. The witness screen was not hit by any high-velocity fragments and the motion pictures showed no evidence of lateral ejecta reaching the 10-ft distance. There were, however, three marks on the witness screen which were caused by small (about 1-in.) low-velocity clods. There are, however, high-velocity ejecta from the event but these are limited to trajectories with high initial slopes. These ejecta consist of small pieces of the poly(vinyl chloride) pipe, dust, sand, and small clods of earth. The spent fragments fall back to earth over a radius of some 50 feet from ground zero and are not considered a hazard.

Still photographs taken before and after a shot are shown in Fig. 3. A typical cross-section of the earth after a test is shown in Fig. 4.

The blast wave reached the inter-pipe distance immediately following the appearance of the fireball, as inferred from the response of the witness in the film record. The magnitude of overpressure in the blast wave was not measured.

Deductions from the results of a previous investigation (2)

(2) T. H. Pratt, "An Investigation of Quantity-Distance Relationships for Silo-Type Launch Sites", op. cit., p. 467 (Confidential).

concerning propagation of detonation between missiles in silo-type launch sites indicated that sympathetic detonation will not occur between 5-lbm charges at 10 feet. This conclusion is borne out by an independent estimate of the distance, d, in feet, necessary to prevent the underground propagation of an explosion from the detonation of a mass, W, in pounds, according to the relation (3)

$$d \geqq 1.5 W^{1/3}$$

(3) J. A. Butas, Safety Division, Installations and Services Office, U. S. Army Missile Command, private communication, Jan. 1966.

From this equation explosions will not propagate between 5-lbm charges beyond 2.6 feet. Therefore 10-ft spacing of sites is more than adequate.

25-lbm Tests - The safe storage of 5-lbm lots of explosives having been successfully demonstrated, further experiments were done to explore the upper practical limits of this type of storage. In preliminary tests a 10-ft-deep, 10-in. -diam. hole gave crater formation with a $37\frac{1}{2}$-lbm charge of Composition C-4; the same holes with 25-lbm charges gave camouflet formation but with extensive residual upheaval (Table I, Shots 1, 2, and 3).

Fig. 5 shows the test site before Shot 3. As in the 5-lbm series fiducial stakes 18 inches high were spaced 3 feet apart; however, in this series the center stake was 3 feet from the center of the hole. Plywood witness screens, 4 ft × 8 ft × $\frac{1}{4}$ in., were erected 10, 15, and 18 feet from center; unlike that shown in Fig. 1, the kraft paper was omitted and the plywood was mounted on the front face. An 18-in. -diam. × 27-in. polyethylene drum suspended 30 inches above the ground at 15 feet and containing 150 lbm of water served as an anthropomorphic dummy. (The white rim of a not-yet-trimmed liner for a later shot is seen in the background.) Fig. 6 is the post-firing view of Shot 3, showing the extent of surface dislocation; the nearest screen (at 10 feet) is characteristically pulled in toward the source by rarefaction.

Although the results with 10-ft holes were marginal, this series of shots demonstrated that any unsupported liner extending above the surface could be impelled sufficiently energentically to penetrate the witness screen (Shot 2) and that gravel at the lip of the hole will also be accelerated enough to dent the witness screen and constitute a hazard to persons standing as close as 15 feet. Remedial steps (see below) have proved satisfactory.

Proof shots were made in 12-ft-deep holes with 25-lbm charges (Table I, Shots 4-7). In all, four tests were performed: 3 in plastic-pipe-lined holes and 1 in an unlined hole. In the course of this series, both Composition C-4 explosive and RH-P-112 plastisol-nitrocellulose composite propellant were used. In addition, an attempt was made to observe whether the direction of propagation of detonation in the charge is significant.

The test in the unlined hole (Shot 4) with an 8-in. -diam. × $8\frac{1}{2}$-in. -long C-4 charge resulted in a camouflet formation; the negative phase of the surface blast ripped off plywood witness screens at 10 and 12 feet from the mouth of the hole but left intact at 15 feet a similar screen, as well as the water-filled plastic drum.

Table I

Below-Grade-Storage Proof Tests

Shot	Charge,[a] lbm	Hole Depth[b], ft	Result	Camouflet Diam.[c], ft	Permanent Surface Displacement Diam., ft	Permanent Surface Displacement Ht., ft	
1	37½	10	Crater	--	7[d]		
2	25	10	Camouflet	e	12	2	Witness screen at 10 ft still erect; perforated by liner fragments at knee height.
3	25	9	Camouflet	e	12	2+	Screen at 10 ft pulled in and broken by rarefaction wave; screens at 15 ft and 18 ft dented by gravel. Suspended dummy at 15 ft intact. One-ft^3 clod heaved 47 ft.
4	25	12[f]	Camouflet	4½	8	1½	Gravel collar displaced to 18-ft diam. Screens at 10 ft and 12 ft pulled in; screen at 15 ft erect; no gravel marks. Suspended dummy at 15 ft intact.
5	25	12	Camouflet	6	9	1	Screen at 10 ft pulled in.
6	25[g]	12	Camouflet	<6½[h] 5½	6	¾	Screen at 10 ft pulled in. Standing dummy undisturbed.
7	25[i]	12	Camouflet	8	10	1½	Screen at 10 ft pulled in. Standing dummy toppled. Extensive clod formation and fall-back up to 40 lbm and 17 ft from center.

[a] Composition C-4, 8-in.-diam., cardboard-confined; J-2 initiated from top
[b] Polypropylene-lined; 10-in.-diam.
[c] From ground depression after heavy rain
[d] True crater diameter across inner lip edges
[e] Not measured
[f] Unlined; 12-in.-diam.
[g] Bottom-initiated
[h] From probe-rod measurement
[i] RH-P-112 solid propellant

The lined holes contained lengths of 10-in.-diameter × ¼-in.-thick polypropylene pipe; the tops of the pipe were flush with the surface. Around the mouth of the pipe was spread a 2-ft-diameter circle of sand 3 inches deep, in turn surrounded by a 6-ft-diameter annulus of gravel (Fig. 7). Use of gravel was desirable to facilitate surface-water drainage; the inner sand collar was to preclude the possibility of high-velocity particles being spread laterally from the mouth of the pipe in the event of an explosion.

Fig. 8 shows the arrangement for Shot 6 (foreground) and Shot 7 (background). The water-filled carboy was standing free on a steel drum.

In all four cases camouflets were formed. With Composition C-4 (Shot 6), a witness rod driven 11 feet into the ground 3¼ feet from the center of the original hole failed to penetrate the camouflet, indicating a camouflet diameter of no more than 6 feet. Owing to heavy rains between the shot and time of measurement, the camouflet formed with propellant (Shot 7) collapsed and could only be inferred from the dimensions of the caved-in area. A 4-ft-deep depression about 8 feet in diameter was formed, implying an 8-ft camouflet. It was subsequently confirmed that such depressions gave reasonable measures of camouflets, since a 5½-ft-diameter depression was observed for Shot 6. Photographs of camouflet depressions for Shots 5, 6 and 7 appear as Fig. 9, 10, and 11, respectively.

As for above-ground effects, both C-4 and propellant vertically displaced the surface momentarily about 5 feet. Although the apparent diameter of the displaced zone was 12 to 15 feet with propellant and only 10 feet with C-4, in no case was the plywood witness screen at 10 feet struck by ejecta. The dummy was toppled by the propellant blast at 15 feet but only jostled by the C-4 blast; in neither case was the plastic container ruptured or punctured. Fig. 12 gives a post-firing view of Shot 6 (foreground) and Shot 7 (note toppled carboy).

As final points of contrast, the low brisance of propellant as opposed to C-4 resulted in formation of numerous clods as large as 12 inches in diameter which continued to fall as long as 5 sec after charge initiation. The farthest of these clods fell 17 feet from ground zero; the largest found was 40 lbm. There was a 1½-ft-high raised rim around the hole mouth after the propellant shot, while there was almost no permanent rim with the C-4 (Fig. 12). No differences were observed between C-4 charges fired from the top down and one fired from the base upward.

Summation and Conclusions

The results of these tests show that an inadvertent detonation of a potentially hazardous sample of 5 lbm stored in a pipe field consisting of dry wells 6 feet deep on 10-ft centers will be contained by the earth in camouflet formation. Similarly, at 12-ft depths, detonation of 25-lbm charges form camouflets of the order of 8 feet in diameter or less, with surface dislocations about 10 feet in diameter. Evidence from witness screens and motion pictures indicates that in the highly improbable situation of a person at a pipe adjacent to the site of an explosion at the moment of occurrence, he would not be gravely injured by high-velocity ejecta, the resulting fireball, or ground upheaval.

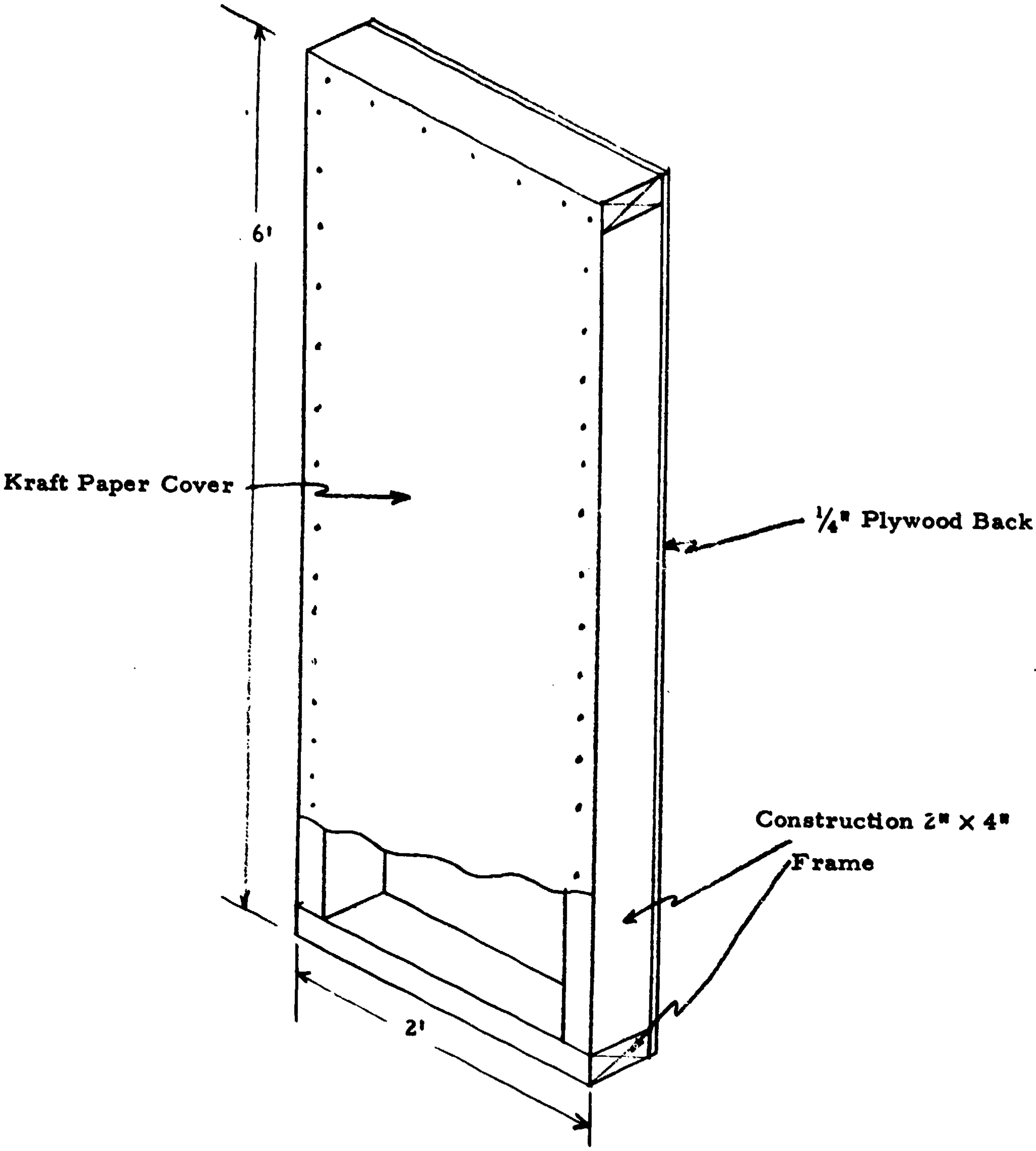


Fig. 1 KRAFT-PAPER—PLYWOOD WITNESS SCREEN

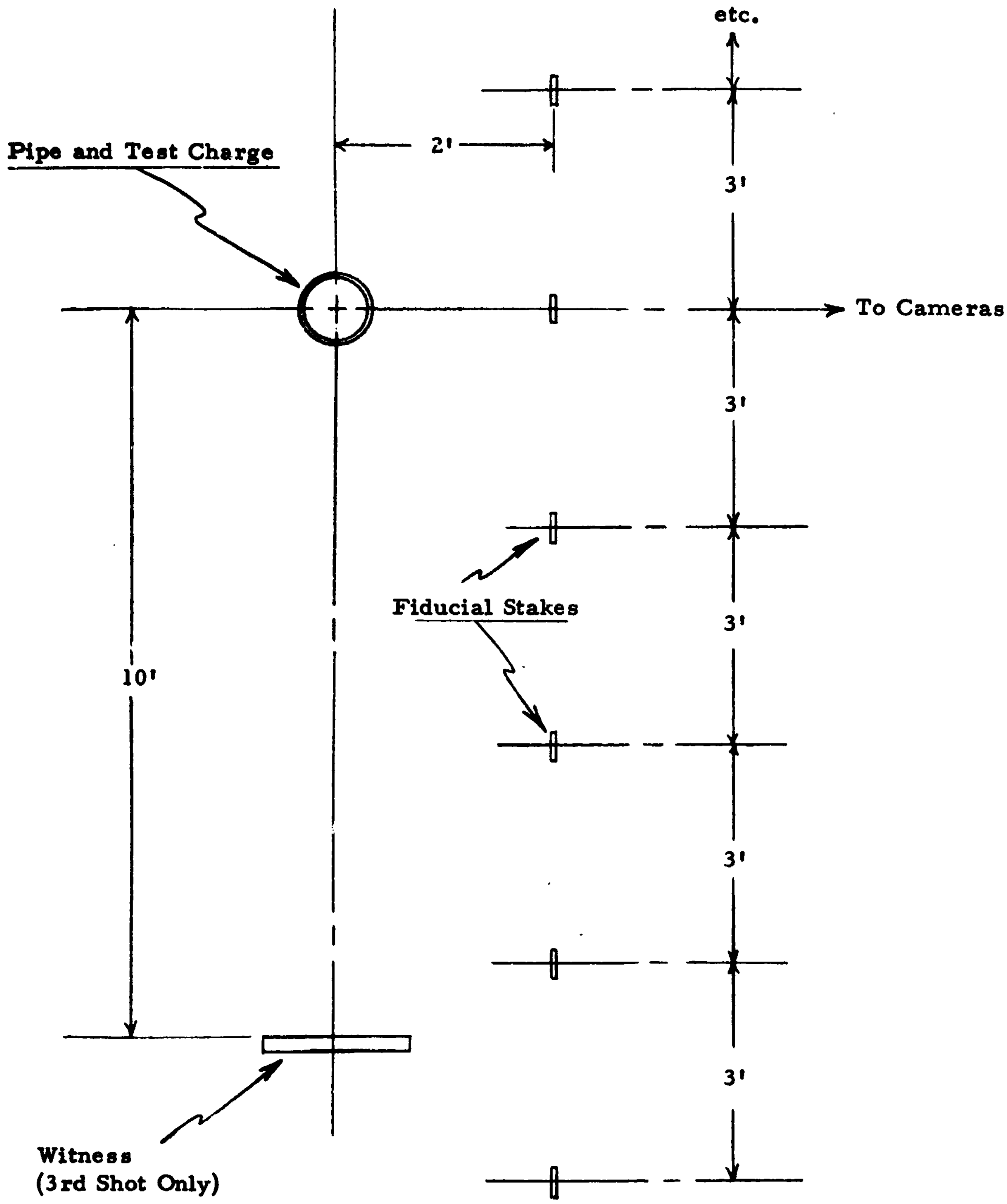


Fig. 2 PLAN OF 5-LBM TESTS

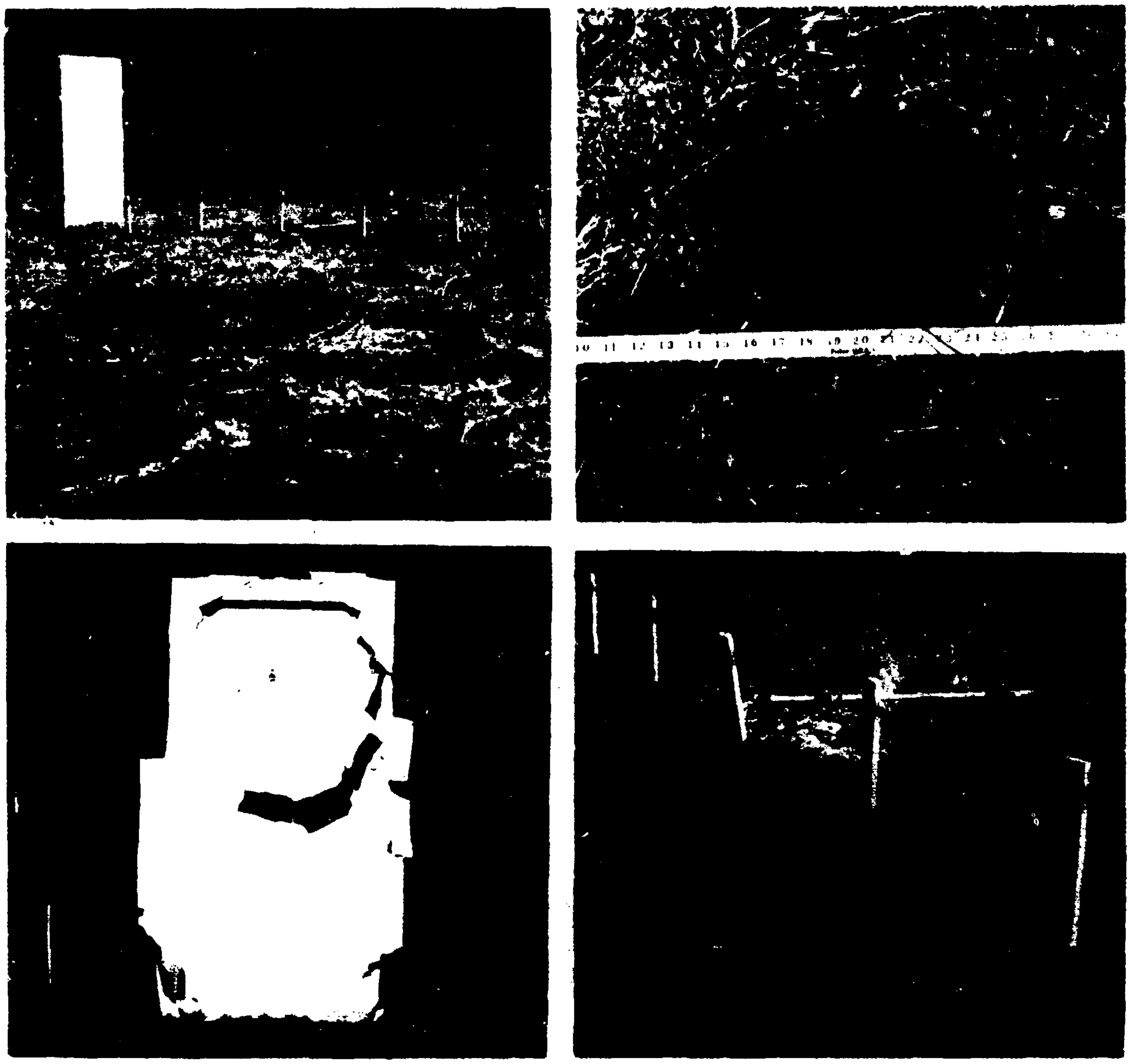
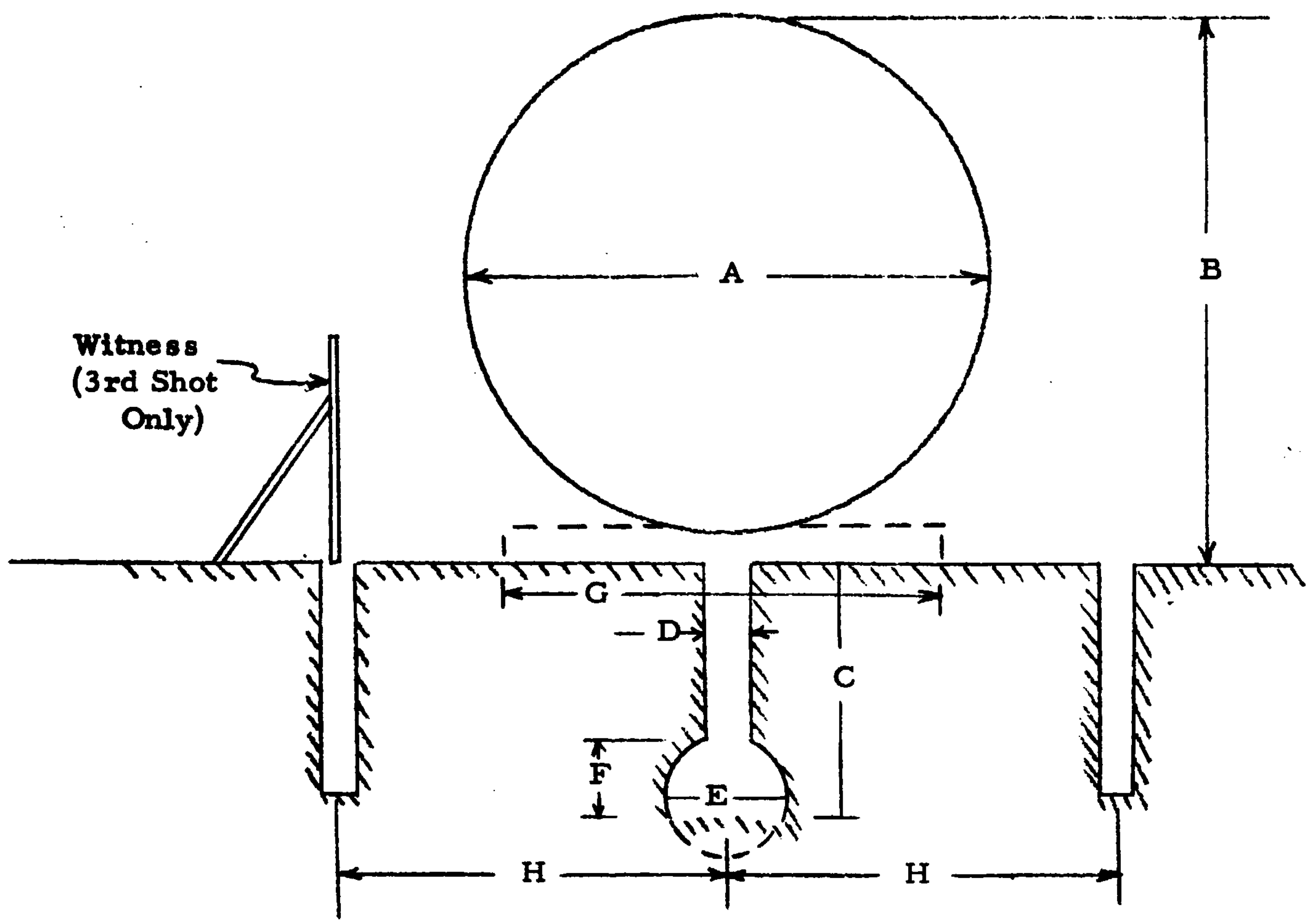


Fig. 3 BEFORE (top) AND AFTER (bottom) VIEWS OF THE THIRD 5-LBM-CAPACITY-PIPE-FIELD TEST (6-FT DEPTH; POLY-(VINYL CHLORIDE) LINER)



A. 13'6" Fireball diameter from t~0.03 sec to t~0.36 sec.
B. Fireball height, 13' at t~0.03 sec to 31' at t~0.36 sec.
C. 6'6" Depth to top of fallback at t = ∞.
D. 16" Final hole diameter at t = ∞.
E. 3' Camouflet diameter at t = ∞.
F. 2" Camouflet depth at t = ∞.
G. 11'6" Disturbed earth diameter (maximum) at t~0.4 sec.
H. 10' Adjacent hole spacing at t = 0 and t = ∞.

Fig. 4 CHARACTERISTICS OF 5-LBM-CAPACITY-PIPE FIELD TEST SHOTS

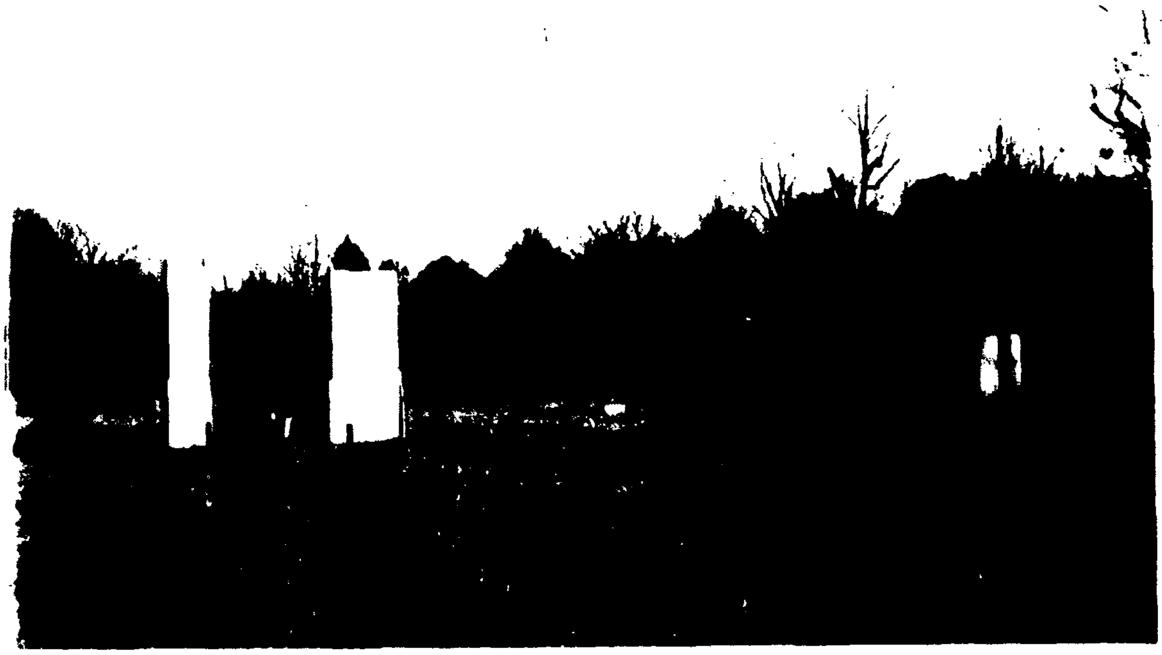


FIG. 5 TEST SITE FOR 25-lbm CHARGE AT 9 FT. (SHOT 3).

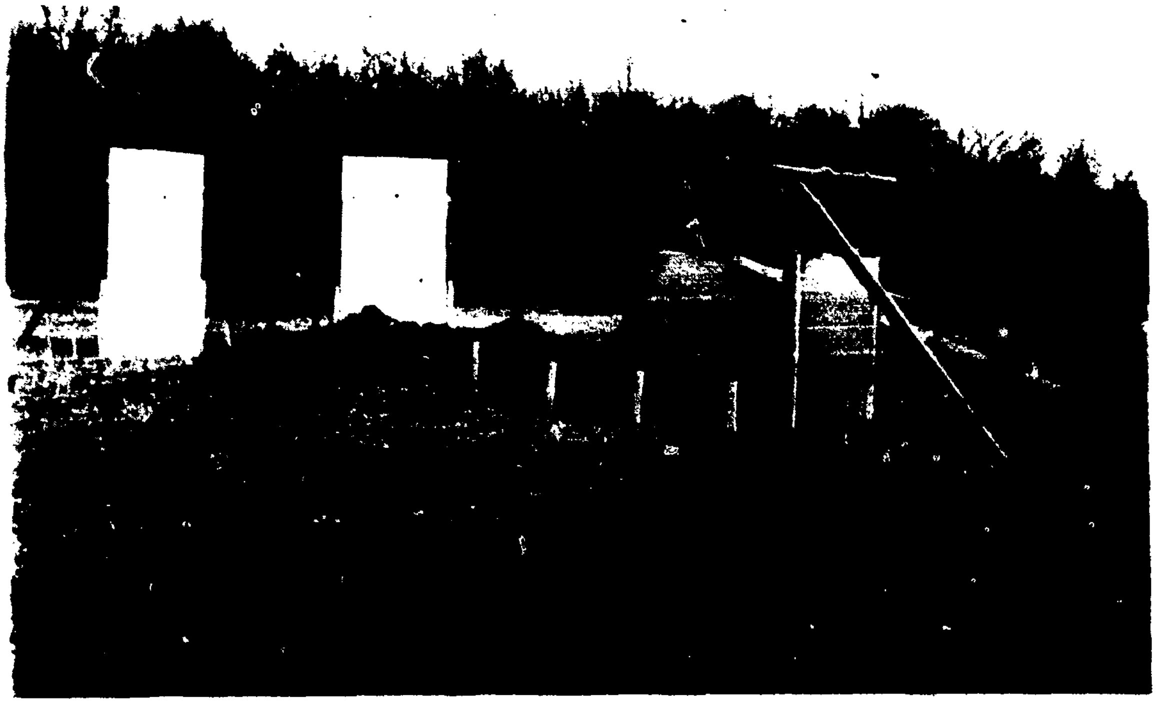


FIG. 6 EFFECT AT SURFACE OF DETONATING 25-lbm OF C-4 AT 9 FT. (SHOT 3).

FIG. 7 SAND AND GRAVEL "COLLAR" ABOUT HOLE MOUTH (SHOT 6).

FIG. 8 TEST SITE FOR 25-lbm CHARGES OF C-4 (SHOT 6)(FOREGROUND) AND RH-P-112 (SHOT7)(BACKGROUND) AT 12-FT. DEPTH.

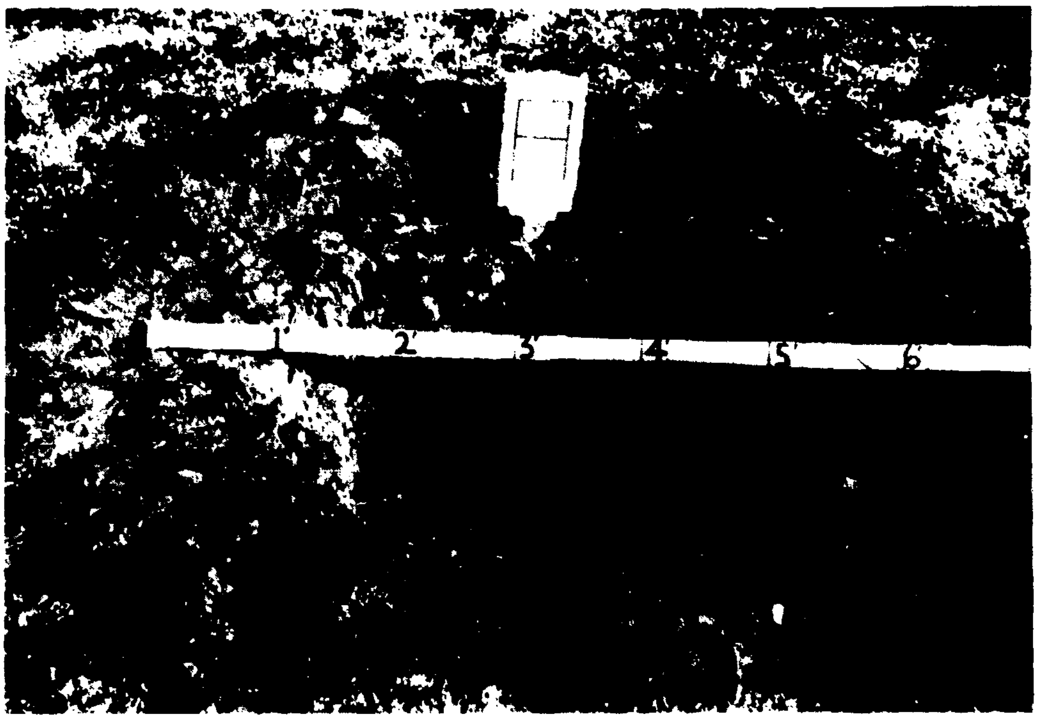


FIG. 9 SUNKEN CAMOUFLET—25-lbm C-4 AT 12 FT. (SHOT 5).

FIG. 10 SUNKEN CAMOUFLET—25-lbm C-4 (BOTTOM-INITIATED) AT 12-FT. (SHOT 6).

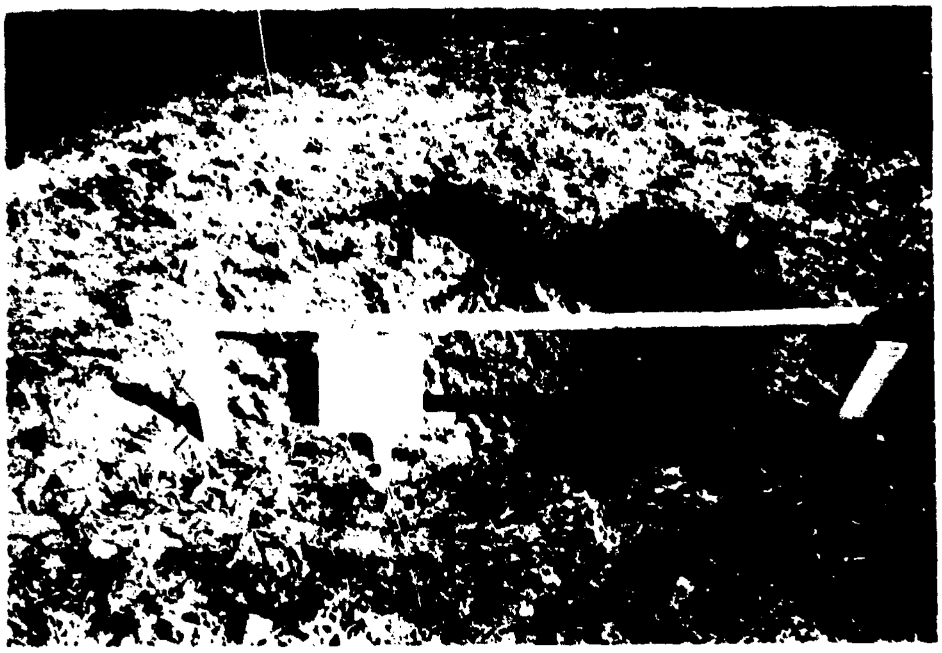


FIG. 11 SUNKEN CAMOUFLET—25-lbm RH-P-112 AT 12 FT. (SHOT 7).

FIG. 12 SURFACE DISLOCATION BY 25-lbm CHARGES OF C-4 (SHOT 6) (FOREGROUND) AND RH-P-112 PROPELLANT (SHOT 7)(BACKGROUND).

DALE, NPP INDIAN HEAD: I'd like to congratulate you on your work. How far apart would you space your 25-pound lots?

PRATT: The design of the thing calls for a 15 ft. spacing. This is a compromise between keeping the pipes close enough together such that the inter-connecting plumbing for the heating field doesn't come prohibitive but still keeps the pipes far enough apart that there is no worry about sympathetic detonation. This is well past any region in which you would get any sympathetic detonation even for sensitive material.

DALE: That's 15 ft.?

PRATT: Yes, 15 feet on centers.

DALE: What kind of a heating arrangement do you have?

PRATT: There is a jacket that goes on the bottom of the pipe that wasn't shown on the first slide and it is steam heated.

STUCKEY, THIOKOL: I want to know how you get the stuff down in there. We used sunken drums and other buried treasure we've had all over the place - you have that thing 10 to 12' deep and it looks like a pretty small pipe and I have some items I certainly wouldn't want to lower down in there unless you have a real good method to do it.

PRATT: As far as the 25-pound facility is concerned, the standing operating procedure and the design of getting the item in and out has not been specified to this date. However, our 5-pound facility which is refrigerated, and our older 1-pound facility that we've had for a number of years - what we do simply is tie a string to a polyethelene bottle in these cases. Also due to the nature of the material that we handle in our SOP, we pull the corks of the bottles before we disturb them. We simply pull the string on the cork and the person has a little remote pulley arrangement that he pulls the bottle back up with, then he can go out in the field and pick it up. But he does do it from a distance, yes.

UNIDENTIFIED: There is the possibility of the string breaking.

PRATT: Yes, I suppose there is always the possibility of the string breaking. But if it does its going to go to the bottom of the hole before it -

UNIDENTIFIED: I don't think you could outrun it if it went to the bottom of the hole.

PRATT: No, I don't think you could. But it is done remotely, a person isn't right over the top of the hole pulling it out.

HARTON, NASA: I was interested in knowing if you had done some testing on the sympathetic detonation, did you actually run some tests to see if other samples would be propagated?

PRATT: Yes, in an earlier program we did some work for the Nike Zeus office on situating silos. What we did on that - it was reported at the Langley meeting I believe - was to set off propellant samples in a silo configuration and we put aluminum rod that had tetryl pellets at various distances and we used these for witness, we could tell from the shape of the rod later if the tetryl went off. One thing that we did find very quickly was that the sympathetic detonation distance for tetryl which is rather sensitive explosive as far as card gap is concerned, has to be inside the crater. If you're outside any cratering formation, you had no difficulty with sympathetic detonation and there's a rule of thumb that people go by. I don't have it on the tip of my fingers right now, but its D mass to 1/3 thing and we're well outside of it.

"HAZARD DATA COMPILATIONS PREPARED AT NOL"

D. C. Hornig, I. Jaffe & N. Holland
Naval Ordnance Laboratory, White Oak

During the past year three compilations which deal with sensitivity tests, sensitivity evaluation and the effects and properties of both explosives and propellants have been completed at the Naval Ordnance Laboratory. These are:

1. "A Manual of Sensitiveness Tests"(High Explosive).

2. "The NOL Large Scale Gap Test. Compilation for Propellants and Explosives II." NOLTR 65-117, 1965 (CONFIDENTIAL).

3. "The High Explosives Handbook - Effects and Properties" NOLTR 65-218 (CONFIDENTIAL).

A Manual of Sensitiveness Tests (High Explosive)

D. C. Hornig, U. S. Naval Ordnance Laboratory, Silver Spring, Md.

Under the Tripartite Technical Cooperation Program, representatives from the United Kingdom, Canada and the United States* have been editing and assembling a manual of tests used in these countries for high explosive hazard evaluation. Some 16 laboratories have furnished factual descriptions of their tests to the editors. The first issue of the manual is now being published.

What purpose will this manual serve? First, it is intended to provide an authoritative source of information on the tests, themselves. Military laboratories have a compelling interest in high explosives. Since it is obvious that no one establishment can or should depend solely on its own people as the source of new ideas, it follows that each maintains a healthy interest in developments, being pursued by others. The detailed methods used for hazard evaluation have not heretofore been available. This made it necessary for any interested laboratory to question the originating laboratory each time a set of unfamiliar test data was acquired. The manual should reduce the need for frequent inter-laboratory consultation.

Second, there are limitations to the conclusions that one can draw from a given sensitiveness test. An experienced worker knows this; it is not always apparent to the newcomer to the field. The manual will help define test limitations.

A third objective of the manual is to stimulate inter-country agreement on hazard evaluation. The authors consider that the three countries should have mutually acceptable standards for the introduction of new service explosives. While it is probably impractical that each country should have exactly similar tests, there should be a correlation in the type of tests used and mutual agreement on the relevance of the data produced by the tests in the three countries.

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* E. G. Whitbread, Explosives Research and Development Establishment, Waltham Abbey, England

G. R. Walker, Canadian Armament Research and Development Establishment, Valcartier, Quebec

D. C. Hornig, U. S. Naval Ordnance Laboratory, Silver Spring, Maryland

The final purpose of the manual is to stimulate improvement in existing tests and to encourage the development of new ones where a clearly evident need exists. If it is not obvious, then let us emphasize those last words - where a clearly evident need exists. There has been a historic tendency for each new worker in the field to devise his own experimental apparatus and procedure, which turn out to be simply variations on a theme. Tests used for hazard evaluation should be related in a rational manner to the theory of explosive sensitivity. New tests ought to measure the response of the explosive to a new stimulus, or response at a stimulus level which has not been previously studied.

When complete, the manual will contain:

1. An introduction to each group of tests
2. Descriptions of test apparatuses and procedures
3. Typical test results
4. A critique on the virtues and limitations of each test

Only parts (1) through (3) will be included in the first printing and they will cover the sensitiveness tests of high explosive to impact, explosive shock, friction, and fragment attack. Parts (2) and (3) were furnished by the users, themselves. Each test should therefore be an authentic description, in sufficient detail so that another laboratory can understand test results without additional explanation.

The introduction to each test category has been prepared by the authors. It describes the main features of the test and explains differences in terminology where these may be confusing. The introduction points out important variations in apparatus or procedure. It also indicates the frequency of use - that is, whether the tests are a part of the daily routine, intermittent, special purpose, etc.

The critiques will be prepared in the future. They will reflect editorial opinion on the value of an individual test or group of tests. The critiques will discuss the factors which affect internal precision and reproducibility. They will attempt to assess the value of each test category as a means of determining explosive hazard. Finally, the critiques will discuss selection of test combinations to give the best means of predicting handling safety. The authors recognize that the manual is not yet all-inclusive. Tests which are

primarily aimed at determination of thermal stability were purposely omitted although one cannot make a complete judgement on hazard without them. Certain categories, for example electrostatic sensitivity, were omitted in order to expedite the first printing of the manual. These deficiencies will be corrected as rapidly ad the work load of the authors will allow.

Members of the Armed Services Explosives Safety Board and of this Explosive Safety Seminar can help make the manual more useful. First, you can advise the authors of omissions or corrections. Second, you can give your criticism and suggestions for improvement.

Distribution of the manual will be automatic to those laboratories that have participated in its preparation by submitting information on their tests and test results. It will also be sent, in limited quantity, to Defense Department administrative activities which have an explosive safety function. Others who wish to have copies will be able to get them on request from the Defense Documentation Center, Cameron Station, Alexandria, Virginia. The manual should be available by September of this year.

When the manual is complete, the next problem to be tackled is one of standardization. The objective will be inter-country agreement on an acceptable pattern of hazard evaluation. As was said earlier, this means the three countries must establish a correlation between tests. The countries must agree that data from a chosen set of tests is relevant and forms an acceptable basis on which, for example, the United Kingdom would approve purchase of weapons containing a newly-developed U. S. explosive.

It is probably unrealistic to expect that even just the activities in the United States who are concerned with the development and service acceptance of explosives will adopt a completely uniform set of sensitiveness tests. Another route to "standardization" does seem possible. First, we can select the types of stimulus which, by experience or judgement, we consider essential to measure. Next, an interchange of standard samples and round-robin testing by a group of interested laboratories should establish a pattern of results between the laboratories involved. The final step

is to apply a non-dimensional, co arative scale - where necessary - to the test measureme .s. Those of you who are familiar with the British "Figure of Insensitiveness" know how they use this means to even out variations between tests and between laboratories. The idea was treated in a little more detail in a paper* presented 3 years ago at the International Conference on Sensitivity and Hazards of Explosives.

Without question, the Armed Services Explosives Safety Board and its interested members can help the TTCP Working Group effort. We need the support of all who have a stake in the safe use of explosives. If you are convinced, as I am, that agreement on testing can be reached and that the necessary inter-laboratory correlation can be done, then the Working Group will have a good chance of success.

* Standardization of High Explosive Sensitiveness Tests, D. C. Hornig, Proceedings of the International Conference on Sensitivity and Hazards of Explosives, London, 1963.

"The NOL Large Scale Gap Test ... Compilation for Propellants and Explosives II." NOLTR 65-117, 1965 (CONFIDENTIAL).

The shock sensitivity of explosives and propellants, their measurement by the standardized NOL large scale gap test, and interpretation of the data are discussed in detail. The present procedure as well as the best test calibration, gap thickness vs gap pressure, are presented. A sister test, the extended gap test, which uses the same calibration, and which can be used to study low impulse reactions of granular materials (e.g., NH_4NO_3, NH_4ClO_4) is also described.

Included in the report is a complete compilation of all the gap test results obtained at NOL on propellants and explosives. These are used to illustrate the change in shock sensitivity with propellant composition as well as the effects of confinement, temperature and porosity on the shock sensitivity.

The effects of changing the gap test variables such as the donor, gap material or the witness plate are also discussed.

This report supercedes NOLTR 61-4. That portion of the report which is unclassified is to be published in 1967 in the Proceedings of the 36th International Congress of Industrial Chemistry in Belgium under the title of "Shock Sensitivity of Solid Explosives and Propellants" by D. Price, I. Jaffe and G. E. Roberson.

"The High Explosives Handbook - Effects and Properties"

NOLTR 65-218 (CONFIDENTIAL)

This report contains charts, graphs, and nomographs showing the effects of explosions as functions of such variables as charge composition and weight, distance from explosion, etc. The major portion of the report deals with effects of explosions in air and underwater; several pages of effects of fragmenting weapons and tables of explosive properties are included. In many cases the explosion effects are shown in the form of nomographs which can be readily used for different explosions and charge weights.

It is designed for convenient use by the engineer or field worker who is interested principally in the application of the data. The explosive effects parameters will be useful in the design of protective shelters, and the handling and storage of explosives. Although this handbook is mainly concerned with high explosives, the information may be helpful in establishing upper limit load values to launches and vehicles in the vicinity of a missile or rocket whose propellant may accidentally detonate during firing.

The report updates an earlier report, "Explosion Effects Data Sheets" NAVORD 2986, (that was widely used) to reflect knowledge acquired during the past decade. Nomographs have been changed to a more usable form. New explosives and their properties have also been added.

As in the case of the Manual of Sensitiveness, any correction or additions to the last two compilations will be gratefully received.

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CONTROLLED DESTRUCTION OF ORDNANCE ITEMS

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SUMMARY

The feasibility of the concept which uses hypergolic liquid propellant fuel and oxidizer to obtain a controlled flame temperature for destroying the contents of an Igloo storage facility was successfully demonstrated.

The hypergolic propellants selected were inhibited red fuming nitric acid (IRFNA) and unsymmetrical dimethyl hydrazine (UDMH). Upon initiation, the temperature surrounding simulated weapons (55 gal sand filled drums) immediately rose to approximately 2400°F and remained relatively constant for the 22-1/3 minute test. Higher or lower temperatures can be achieved by changing the oxidizer-to-fuel (O/F) ratio, thus changing the flame temperature.

It is recommended that the new concept using liquid propellants for emergency destruct purposes, which has been successfully demonstrated, be extensively explored to meet a variety of requirements to which this concept can be readily adapted.

INTRODUCTION

The objective of the Weapon Destruction System Program was to evaluate the concept of using liquid propellant fuel and oxidizer to obtain a controlled flame temperature for destroying the contents of an Igloo storage facility.

The objective of this program was accomplished by testing in an existing Igloo storage facility (26 x 60 ft) using 55 gal oil drums filled with sand to simulate the weapons to be destroyed. It was desired to heat the area surrounding the simulated weapons to a temperature ranging from 2400°F to 2500°F within 20 minutes and then maintain the 2400°F to 2500°F temperature for 20 minutes. The Propellants, inhibited red fuming nitric acid (IRFNA) and unsymmetrical dimethyl hydrazine (UDMH), were selected for this application because they are completely storable, ignite upon mixing, are unaffected by temperature variation from -65°F to +160°F, and are compatible with standard materials of construction. The combustion temperature can readily be adjusted by varying the mixture ratio (O/F) of oxidizer to fuel. Further, these propellants are currently being used by the Armed Services in prepackaged missiles.

The destruct system consisted of a pressurized nitrogen vessel, actuating valves, fuel and oxidizer tanks and injectors, which were "off-the-shelf" items adapted to this test in an effort to minimize cost and to expedite the program. Upon initiation, the two propellant tanks were pressurized simultaneously and the propellant flowed through the injectors. When the two propellant sprays mixed, hypergolic ignition immediately took place and combustion continued for the desired duration. For the purpose of determining feasibility, eight drums were instrumented and subjected to the direct flame.

The test program included the following:

a. Exploratory tests to confirm theoretical calculations of propellant mixture ratio and flow rates.

b. Simulated Igloo test in a 10 ft cubical to check out injector pattern and position, flow rates, O/F ratio and ability to attain approximate temperature for at least 20 minute duration.

c. Igloo system feasibility test at the Igloo Farm, Pedricktown, New Jersey (system design dependent upon a, and b, above).

TECHNICAL DISCUSSION

Exploratory Tests

Theoretical calculations were made which determined the O/F ratio to be between 0.834 and 0.860 in order to obtain a flame temperature of 2400°F to 2500°F. A test was made to experimentally determine the relationship between O/F ratio and flame temperature using a tube assembly injector. A series of six tests gave results which indicate reasonable correlation with the theoretical data. An aluminum injector was then designed to accommodate the flow rate and to give a uniform wide angle spray pattern. It consists of two fuel fan sprays impinging on the oxidizer fan spray. Results from four tests were satisfactory and the design was accepted for the Igloo system. These tests pointed out that precise control of the low flow rate which determines the O/F ratio and flame temperature is difficult if tank pressure and injector pressure drop are relied upon for control. Therefore, cavitating venturies in the injector lines were used in subsequent tests to maintain control and measure flow rates.

Simulated Igloo Tests

The information gained in the preliminary test phase was transferred into a design for simulation testing. A prepackaged propellant feed system was assembled and installed adjacent to the 10 ft cubical test magazine as shown in Figure 1. The injector head was installed inside the magazine at a height of 7 ft and approximately 6 ft from the 55 gal drum. The sand filled drum was instrumented with three thermocouples for determining the temperature.

The first test, although mechanically acceptable, was not satisfactory in that the maximum temperature achieved was only 140°F and it was stopped after approximately 15 minutes. Examination of the injector showed the surrounding temperatures to be at the melting point of the aluminum. It was also evident that the spray pattern was nonuniform and this was found to be caused by foreign matter obstructing the orifice in one fuel injector. The next test incorporated a higher flow rate and higher O/F ratio to increase the flame size and temperature. Also, the injector head was placed one and a half feet from the drum and one foot above the floor and the injector was angled to fully envelop the side of the drum with flame. This test, which lasted 23 minutes, was a success. A temperature vs time plot obtained from the injector side of the drum is shown in Figure 1. The temperature immediately rose to 1570°F and leveled off at the 1700°F region. The temperature on the side opposite to the injector was steadily climbing and had reached 460°F at shut down. This test indicated two deficiencies: a.) temperatures lower than desired and b.) very low temperature on one side of the drum; both of which could be corrected by increasing the O/F ratio and adding a second injector on the opposite side of the drum.

System Feasibility Tests

The design used in these tests was similar to that used in the above tests except each drum was covered with fire from two injector heads which were located 180° apart. An artist's sketch, Figure 2, shows the general layout of the test equipment, which includes the tankage (fuel, oxidizer and water), nitrogen cascade pressure source (truck), control room and electronic gear (van) and power generator. The water tank was used for testing convenience and for cooling the Igloo after a test. The power generator was required to operate the van heater, electronic recorders and other equipment needed in exploratory testing. The test installation allowed complete flexibility in carrying out the feasibility demonstration. A final system for field installation would be compactly designed, independent of electrical power, as shown in Figure 3. Fourteen drums, eight of which were instrumented with two thermocouples each were emplaced in the Igloo as shown in

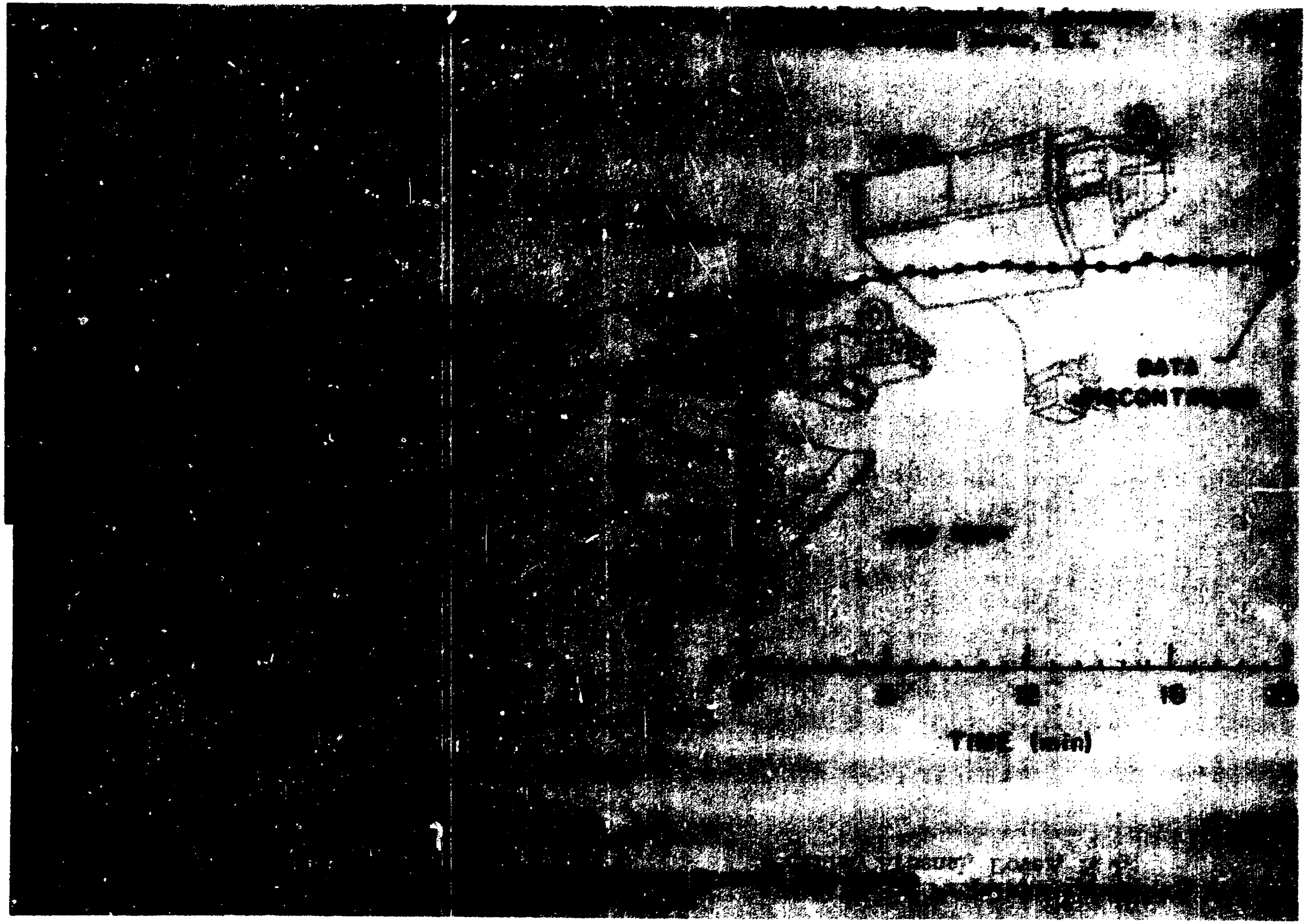
Figure 4. The first test made was unsatisfactory. During the 40 minute test period, temperatures and propellant flow rates varied and excessive smoke bellowed from the Igloo in a pulsating manner. This condition was remedied in the second test by removing the door closure to permit operation at a steady stato condition. The second test, lasting six minutes, was satisfactory and yielded temperatures in the order of 2000°F. These results produced the desired information to allow for a full long duration test. Flow rates and O/F ratic were changed based upon the previous test data and the third test was made. Upon initiation, temperatures immediately rose to the desired level (approximately 2400°F) and held relatively constant for a 22-1/3 minute duration. There was some variation in temperature reading from one thermocouple to another which is attributed to propellant flow and O/F variations caused by fluctuations in line pressure drop and oxidizer tank pressure which could not be compensated by the venturis. The variation would be eliminated in a final design, however, by properly sizing the plumbing design to more accurately meet the pressure requirements. A typical temperature time plot is shown in Figure 5. Results of the fire are shown in Figures 6 thru 9.

CONCLUSIONS

The concept of using liquid propellant fuel and oxidizer to obtain a controlled flame temperature for destroying the contents of an Igloo storage facility was evaluated and feasibility demonstrated. Temperatures in the order of 2400°F were generated in the area surrounding the simulated weapons and maintained constant for a 20 minute period. Warm-up time was less than one minute - which is considerably less than the allowed maximum of 20 minutes. Higher or lower temperatures can be achieved by changing the flame temperature by changing the O/F ratio.

RECOMMENDATIONS

It is recommended that the new concept using liquid propellants for emergency destruct purposes which has been successfully demonstrated be extensively explored to meet a variety of requirements to which this concept can be readily adapted.


DATA
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TIME (min)

Liquid Rocket Propulsion Laboratory
Picatinny Arsenal, Dover, N. J.

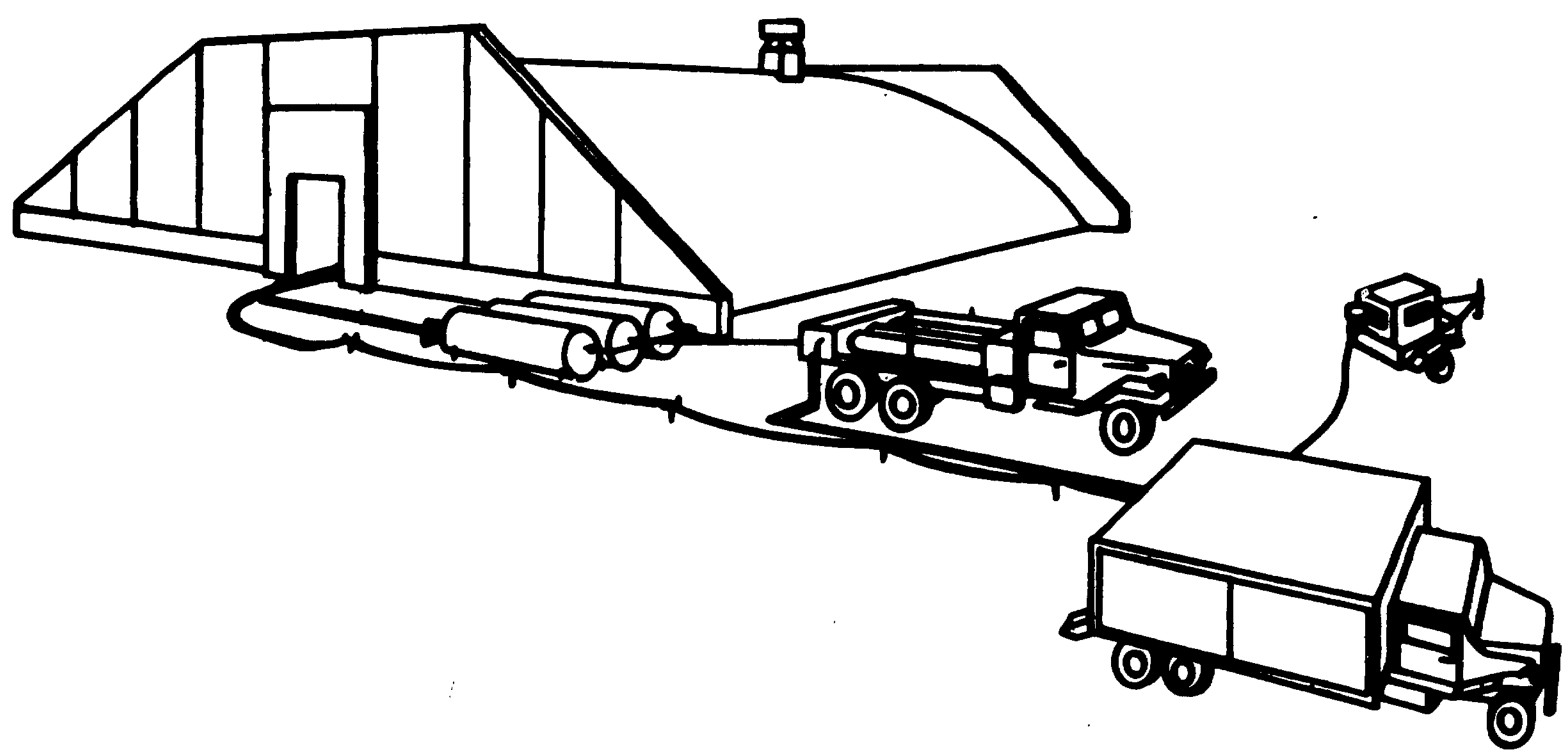

Fig 2. Igloo Storage Destruct System Field Test

Fig 4. Igloo Interior Condition Before Testing

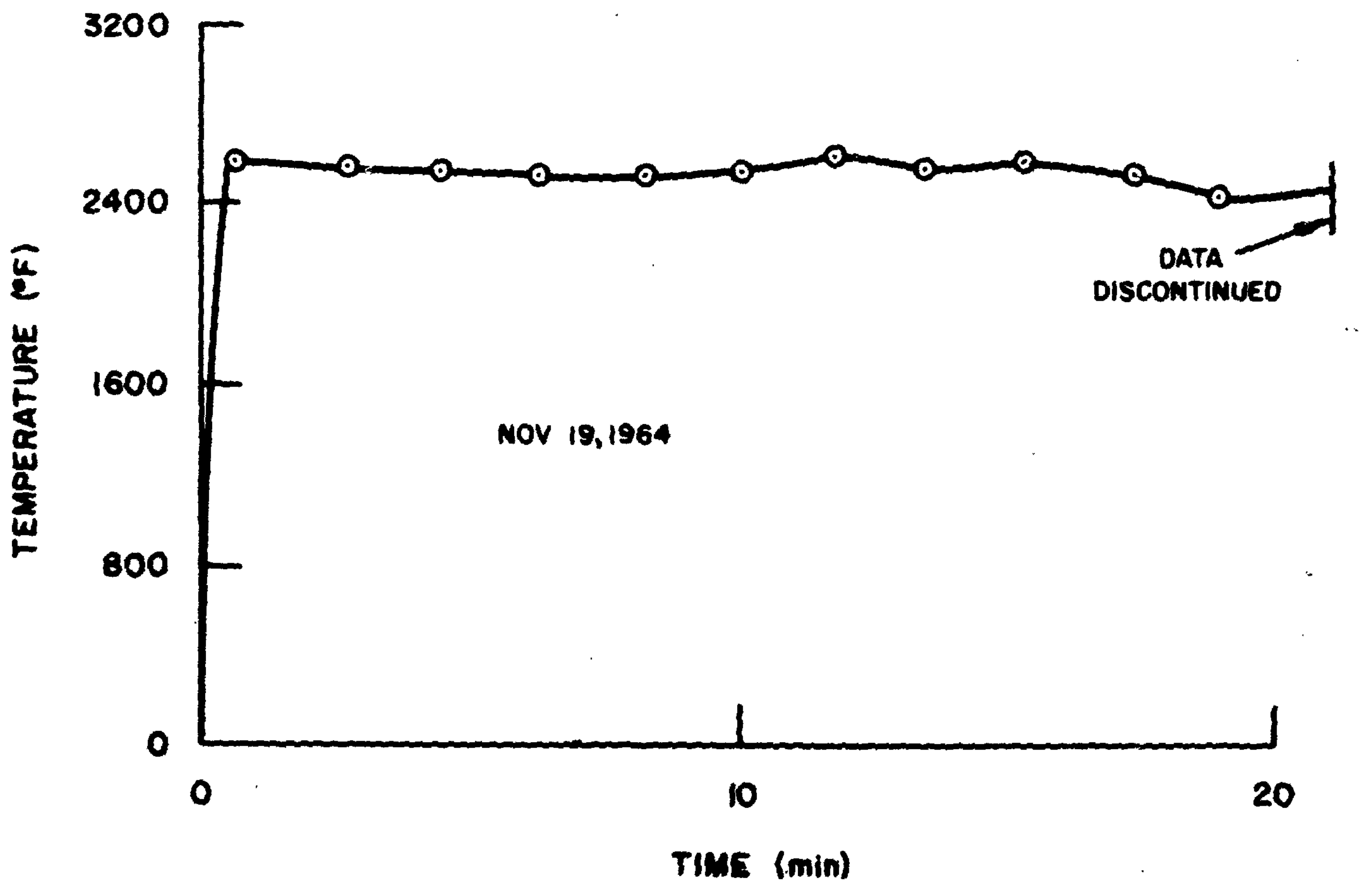

Fig 5 Typical Temperature vs. Time Data obtained in Igloo Test

Fig 6. Igloo Interior Condition after Testing

Fig 7. Side View of Injectors and Drum after Testing

Fig 8. Top View of Injector and Thermocouple after Testing

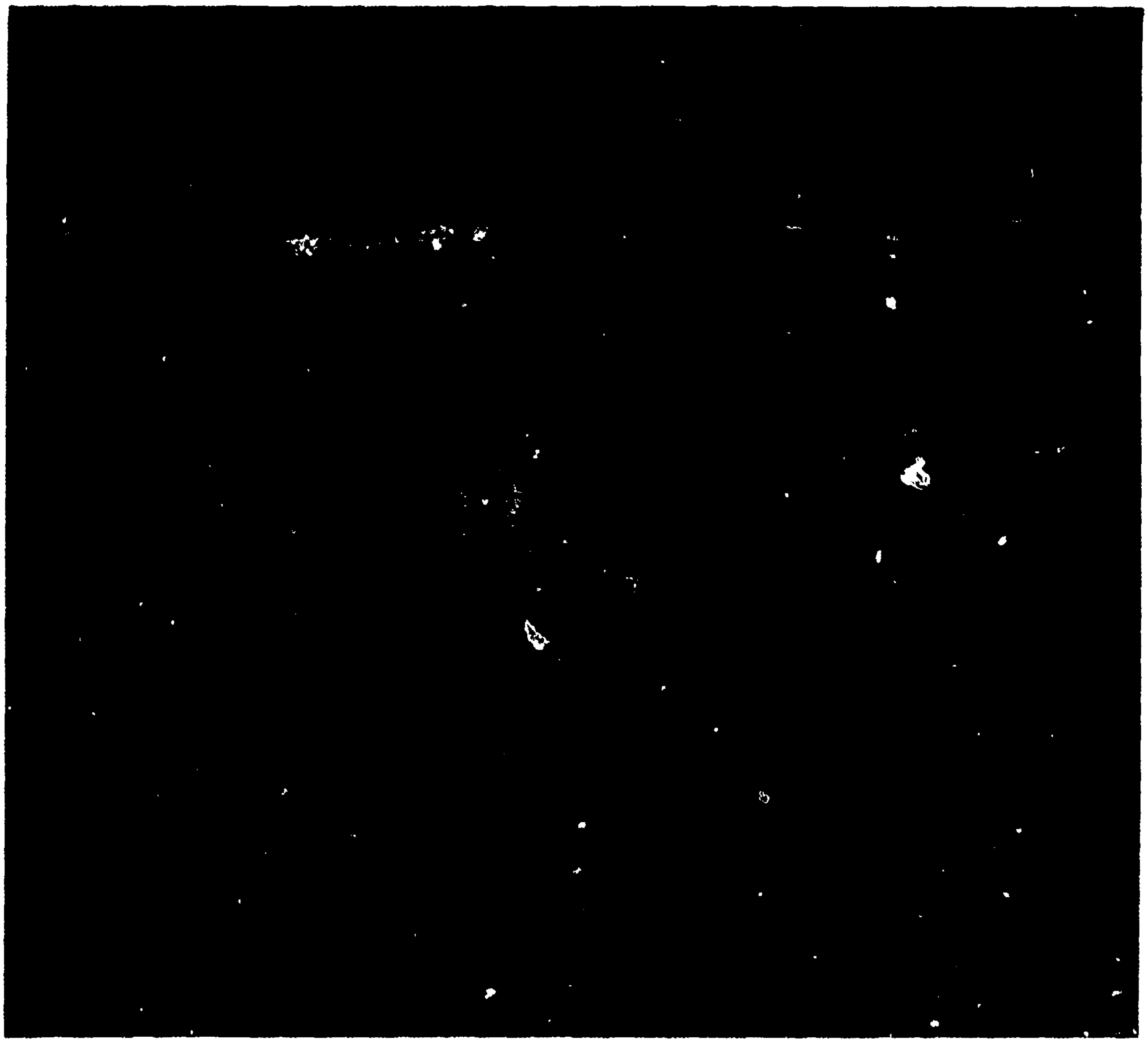

Fig 9. Close-Up of Injector after Testing. Injector was Unaffected by the Heat.

LANDAU, NOTS: I'm not sure exactly what you're trying to do.

BUCKLEY: This was trying to show by using liquid propellants that it would be feasible to take any type of weapon and by just using fire, burn a hole thru the side and either melt out the propellant that way or just destroy the weapon so that it couldn't be utilized by anyone else. We didn't go into any live tests for this feasibility program.

PERKINS: May I add a comment to this, Mr. Buckley, so that Mr. Landau will understand a little more fully. We can't answer your question fully at this seminar because of classification and "need-to-know." However, its purpose was to investigate a possible method of destroying material on very short notice in place in a magazine when one did not have time for the conventional methods of demolition, destruction, or disassembly.

DEESE, NASA: Did you have any toxic problems?

BUCKLEY: We didn't have any problem at the test site. I must admit we didn't go in immediately after the flame was out, not because of the fumes but rather because of the intense heat. It was several hours before we were even able to go into the doorway. As far as the gases that were produced, they pretty well went up the smokestack at the back of the igloo and on up thru the atmosphere and were dissipated by the wind. There weren't any major clouds of smoke that traveled any great distance.

CHELKO, NASA: What were your propellants and what were your oxidizers and why didn't you have separation walls between them and all of the other things that generally go between oxidizers and propellants? Were they hypergolic propellants?

BUCKLEY: They were hypergolic propellants, inhibited red fuming nitric acid and UDMH.

CHELKO: How close were your storage tanks to one another?

BUCKLEY: The storage tanks were within a few feet.

CHELKO: And the control van was how far away?

BUCKLEY: The control van was about 100 feet away. This was all stored under low pressure. There is no danger in a test of that nature.

CHELKO; Except during fill times, when you're filling up your tankage?

BUCKLEY: They weren't filled up at the same time.

THE ROLE OF DCAS IN THE ADMINISTRATION OF SAFETY IN CONTRACTOR PLANTS

by
Lt. Col. H. R. Kain, USAF
Defense Contract Administration Services
Alexandria, Va.

Today I plan to take a few minutes of your time to discuss the Defense Contract Administration Services. I plan to tell how we were born, what we have accomplished, and our future goals. The colloquialism DCAS is usually used to identify our organization. Our headquarters is located at Cameron Station, Alexandria, Virginia. Mr. Robert McNamara, our Secretary of Defense directed that good management of contracts could best be obtained by maintaining a "single face" to industry. The vehicle to accomplish this was Project 60 which was established in July 1962. DCAS developed from a gleam in Mr. McNamara's eyes to a budding infant in April 1964, when a pilot organization was established in Philadelphia. The lessons we learned in Philadelphia were applied to the other DCAS regions. We now have eleven DCASRs, which are located in (Chart 1) Boston, New York, Philadelphia, Atlanta, Chicago, Detroit, Cleveland, St. Louis, Dallas, Los Angeles, and San Francisco. We have 23 DCASDs. These are District offices.

Initially our mission was obscure. We were responsible for the administration of the safety aspects of contracts for nonhazardous material. (Parenthetically, I might add we never were sure what this encompassed.) On April 20 of this year we were assigned the responsibility of administering all aspects of contracts assigned to DCAS for contract administration, regardless of whether the in line or end product was hazardous, dangerous or non-hazardous. We have established Specialized Safety and Flight Operations Divisions in each of the eleven regions and in several Districts. We manned these divisions with military and civilian specialists. In each Region, we have a qualified military pilot designated as Chief. He is supported by one or more civilian Safety Engineers and Safety Officers. These civilians, for the most part, were trained by you people in the Military Departments. As you leave here today, we will give you a handout showing the military chiefs, their civilian professional assistants, their telephone numbers, and addresses.

We are upgrading our staff by sending them to the various military schools to keep them attuned to the latest developments in the field.

DCAS was a marriage of segments of the Offices of the Inspectors of Naval Material, Army Procurement Districts, and Air Force Contract Management Regions. The skills possessed by these three military procurement contract administration and management organizations were welded into DCAS.

Several of the Safety Engineers in this room today, contributed to the growth of DCAS. These men from the Armed Services Explosives Safety Board, the Army Materiel Command, the Air Force Logistics Command, the Air Force Systems Command, and the Naval Ordnance Systems Command, gave us a wealth of advice, assistance and I might add, at times, commisserated with us. With their professional guidance DCAS grew.

Let's look at the Big Picture which depicts how DCAS now operates. When material is required, one of the Military Services usually issues an Invitation to Bid. From the IFB's received, a selection of a source of supply or a manufacturer is made. Before the contract is let, a team representing the Contracting Officer usually visits the contractor's plant or facility, to make a pre-award survey. The pre-award surveys are now being performed by DCAS teams with a safety representative usually serving as a member of the team. The pre-award team makes a recommendation to the Contracting Officer, whether in the team's opinion, the contractor can perform the contractual requirements. If the team recommends the award, the contract is let. Safety of the contractors plant, the methods he intends to employ to complete the contract, all play a part in the ultimate award of the contract.

During the course of the contract, the Chief of Specialized Safety or his representative will visit the plant to insure the contractor is complying with the safety aspects of the contract. Quality Assurance Representatives will also be in the plant checking on compliance with the quality of the item being produced.

Perhaps you are saying, "Why is the Government so concerned about safety?" I would like you to know that we are not "do-gooders." We are concerned with the following important aspects of contract administration:

a. Is the contractor complying with the safety aspects of the contract. He bid on the entire contract which includes the safety aspects. The contractor knew the safety aspects when he bid. The Government only expects that he perform in accordance with the contract.

b. One of our main interests is to get the product produced within the framework of the time schedule. There are men in the undergrowth of Southeast Asia who cannot wait for products. Explosions, fires, and accidents seriously delay production and impede delivery. Is your son in Vietnam waiting for ammunition or other implements to restore peace in the world? If he is, you have a personal interest in getting production on schedule. We are concerned for all the boys in Vietnam, Korea, or elsewhere in the world striving to bring peace back to this mixed up world of ours. The contract was written to minimize accidents, explosions, and incidents, and to get the material into the hands of our boys fighting for peace. Our staff is continually surveying to insure this objective is met.

c. The President and Congress has repeatedly expressed that every effort must be taken to get materials produced on schedule. They have said the Government personnel, contractor personnel, and the general public must be protected. The contract was written with this quest for protection in mind. We are surveying to insure this objective is met.

I would like you to know that we believe that the contractor should run his own safety program. Mr. Contractor, we will not tell you how to run your safety program. We will tell you when you are in violation of your contract or are endangering the lives of our people or when you are taking action which will jeopardize the timely completion of your contract. We do not intend to "nit-pick," but, we expect that as responsible contractors, you will comply with the safety aspects of contracts.

Up to this point, I have discussed our organization and mission and given you some idea of our operations. As many of you are well aware, the pertinent point of exactly what the Government expects and what criteria we will use to determine a contractor's safety capability has been glossed over. When the Defense Contract Administration Services was established, it was readily recognized that there were rather large differences among the manufacturers and services, not only in contractual coverage, but in philosophy and interests. When we in DCAS met with the Military Services in an attempt to standardize the DoD and NASA safety requirements, we were extremely conscious that in the past, numerous activities have performed safety surveys at a facility and at times came up with different conclusions.

These differences created confusion, exasperation and were costly in providing time and personnel in conducting and replying to the various surveying agencies.

To correct the situation recognized both by the contractors and the military, action was taken to establish a work group charged with the responsibility to provide standard safety requirements and criteria. This group is chaired by Mr. Hy Ackerman of our office. I have personally had a preview of the actions of the committee, and so far they are doing a fine job.

Mr. Ackerman who has spent over 20 years in safety for the Army, Air Force, and now DOD, is with us today and has consented to briefly give you a progress report of actions taken by the committee and what is the status of proposals and actions and what we may expect as the final result.

Hy, will you please say a few words.

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Mr. Hy Ackerman
Defense Contract Administration Services
Alexandria, Va.

In July 1965 a letter was received by the Chairman of the Armed Services Explosives Safety Board from the Solid Propellants Safety Group of the Aerospace Industries Association. This letter brought into strong focus the problems of safety in procurement matters concerned with explosives, propellants, and other dangerous materials within the Department of Defense. As Col. Kain has mentioned, the introduction of Defense Contract Administration to administer those contracts assigned to DCAS brought forth additional requirements and problems. These factors too had previously been brought to the attention of DOD.

In September 1965 the Military Departments and Defense Supply Agency by memorandum from Assistant Secretary of Defense (I&L), Mr. Ignatius, were requested to re-evaluate the situation as it pertained to safety responsibilities for contractual obligations. He requested all views to be presented for consideration.

By January 1966 replies had been submitted to DOD from the Military Departments concerned and meeting was attended by Col. Sam Miller, Director of Contract Administration from the Office of the Assistant Secretary of Defense (I&L). This meeting was to evaluate and discuss the replies provided to the Assistant Secretary of Defense memorandum referenced previously. Specific conclusions and agreements were generated at this meeting as follows:

1. The need for an AdHoc work group to obtain additional data to resolve existing problems. ASPR Clauses.

2. Requirement for universal safety, health documents acceptable to Military Departments and Defense Supply Agency as supplements to Armed Services Procurement Regulations.

3. Provide an interim decision on DCAS responsibility for plant safety.

On 20 April, Mr. Ignatius, Assistant Secretary of Defense (I&L), signed two memorandums addressed to Military Departments and Director of the Defense Supply Agency.

One assigned total safety responsibility to DCAS for those plants under their cognizance in consonance with the similar responsibility assigned to the Military Departments over the plants under Military Department cognizance.

Memorandum No. 2 established the DoD work group for the purpose of preparing the following documents:

1. Uniform contract clauses for the Armed Services Procurement Regulations.

2. A single DoD safety publication.

On 16 May 1966, representatives of the Air Force, Mr. Ken Nogales substituted for Mr. Cordova; U.S. Army representative, Mr. Lee Deans; U.S. Navy representative, Mr. Sigismund Brzezinski; and Mr. Romie Kieke of the Armed Services Explosives Safety Board convened into a work group. I represented the Defense Supply Agency and chaired this committee in accordance with the ASD memorandum. We reviewed our authorizations from the Office of the Assistant Secretary of Defense and came to an agreement as to our procedures. We are preparing clauses for inclusion in the ASPRs as standard DoD safety requirements. We also agreed to prepare safety requirements which are uniform and acceptable to the Military Departments. We found that one manual alone would not only be voluminous but most difficult within our time frame to compile. An approach to this problem was to utilize existing publications (tri-Service, if possible) and identify these as ASPR supplements to the safety clauses.

Example: Safety Supplement for the Storage and Handling of Liquid Propellants (old DDRE Manual, AFM 160-39).

Safety Supplement for the Packaging and Handling of Dangerous Material for Transportation by Military Air (AFM 71-4, DSAM 4145.3, TM 38-250, NavWeps 15-03-500, MCOP 4030.19).

As stated previously these manuals are already tri-Service and DSA Manuals. All we are recommending is that an ASPR supplement identification be established for these documents. From the efforts of work group, the manual or supplement for explosives safety is being prepared and will be submitted to the Department of Defense for review and further action for adoption.

We have touched lightly on environmental health hazards. We have requested assistance on this problem from the Surgeon General's office and Bureau of Medicine of the Military and hopefully we will also obtain a supplement regarding the health requirements pertaining to the specific material involved.

The ASPR Committee will provide all concerned with the opportunity to comment after their review, editing, coordination, and clearance with appropriate staff agencies. We are also aware of other activities involved with the preparation of documents, such as, the Inter-Agency

Chemical Rocket Propulsion Group. Hopefully, we will be able to use or modify our documents as the latest information is made available. When will we see these documents officially? Hopefully, by or in six months.

One other feature: we have contacted the Department of Labor and the Department of Interior activities to determine whether an interface can be established at Department of Defense level for other Government agencies for contractor activities.

Are there any questions?

STUCKEY, THIOKOL: This isn't exactly a question, I have a couple of comments. I think by setting this thing up under quality assurance you've set safety back to the stone age. Sometimes I don't even speak to the QC people and that's who I have to work with when you people come into our plants now. Another item that bothers me very much is if you people are going to come in and see what's wrong with us and throw a few rocks, we don't need you. We have manuals, everybody has put out a manual that is supposed to be made for a perfect plant of some type, they always write in the front of the manual someplace that you can get a waiver and anybody who has been out in a contractor plant and tried to get a waiver for the last 10 or 15 years knows that that's just a bunch of words. If you people can do something for us, you'll be a big help and if you can't, I don't know.

ACKERMAN: Basically, we have recognized this problem for several years. Our attempt is to do just that, not to prepare a manual because its DSA. It will not be a DSA manual in any sense of the word. This is an Armed Services Procurement document. Within this document we hope to be able to cure the ills that exist right now. We recognize very definitely that the means of obtaining waivers or deviations have been most difficult and are not identifiable in present procurement requirements. We're hoping to include in a pre-award survey the differences and deviations that exist between the procurement regulations or the safety regulations and the existing plant itself. Then the PCO must accept the existing conditions at the plant if he wants the production from this plant as is or do something about modifying the plant. This determination should be made early in the game, not after you're in production. But even after you're in production, you always find that there are changes in procedural operation that may deviate from the normal standard safety requirements. How do you obtain a waiver or deviation from this means. We have standardized the procedures in this manner too. We hope that the P.C.O. (Procuring Contracting Officer) will give us this; if not, the Military Department responsible for the contract should be able to award that deviation. We are establishing

the flow of correspondence so that it is uniform, its clean, and it won't take six months to a year to answer a problem area. The Defense Contract Administration itself is a Service organization. We are going to try to help you operate in the most efficient manner possible. That's all we do. Basically, the contracts are awarded by the Military Departments and other Governmental agencies. We make that loud and clear. We make it loud and clear that the responsibility of the safety program is the contractors. We are only there to insure that the terms of the contract are being met and try to help you people meet those terms. We're not there to hinder.

JEZEK: I don't know whether you mentioned this or not, but this manual that your work group is working on, will that manual be applicable to Government-owned contractor-operated plants?

ACKERMAN: I think it should be and will be.

JEZEK: If that's the case Hy, what manual is going to take precedence, the AMCR or your manual?

ACKERMAN: Let me put it this way. If the contract is administered by the Military Department, then the AMC Manual will apply for the Army; if its administered by the Air Force, the Air Force Manual 127-100 applies; if its administered by the Navy, the OP-5 manual will apply. But those contractors that are administered by DCAS will be monitored and administered under the terms of this proposed ASPR safety manual.

UNIDENTIFIED: You're talking about a Government facility in the Army. It would really be up to the decision of the Army procuring contract officer what safety requirements he puts in his contract. If the Army has a safety requirement that is considered necessary over and above an ASPR clause of a type, then they certainly would put it in the contract and they often do. And I suspect that the safety requirements for a Government facility would probably be more stringent than the contractor. But your Army procurement agency does have the prerogative of putting whatever they want in the contract.

ACKERMAN: That's right. There has been no question about this. The PCO's of the organizations buying the products make the terms of the contract. We in DSA do not. We administer what exists in the terms of the contract.

HIKEL, BOEING CO.: How do you propose to have these so-called supplements appear. Is this in a procurement clause, a procurement safety specification, or just how will it appear and how will it be disseminated to the procurement agencies of the respective Services?

ACKERMAN: Our approach is this. We would identify these ASPR supplements within the ASPR clauses. For example, we have several ASPR clauses, included in one ASPR clause is the reference to a supplement on the handling of liquid propellants. This proposed supplement to ASPR clause has been an accepted document in the Air Force and by the Navy they have published it as such. It was the old DDR&E manual on the handling of liquid propellants. The Interagency Chemical Rocket Propulsion Group is at present undertaking to rewrite this but we won't get this manual for at least another year. So the best thing I can do is use the old document as a supplement. This gives us as much information as we have up to date. These supplements will be revised periodically. The supplement we have on safety in procurement of ammunition and explosives and other dangerous materials is a compilation of the documents based upon the DoD Instructions. There are no changes in these supplements. The committee has taken what they think are the minimum criteria requirements and included them in the supplements. There's no change to existing criteria. Its considered an excellent document and the Committee members of the Services have agreed upon utilizing this document. It will again be disseminated for comments by OASD or ASPR committee. I think this document and the ASPR clauses are answers to your queries and to your requests for assistance in this matter of procurement. I see no real difficulty gentlemen, I think it will clear up this problem. We don't intend to put another spoke in the wheel which will not assist you people. If it does no good, there will be no additional publication proposed. We hope this procedure will clean up the problem areas we have in the field of procurement of ammunition and explosives and other dangerous material.

MOLLOY, ROCKETDYNE: Does DCAS think they can clean up the situation - we just received a letter from the Air Force saying that they cannot legally enforce the Air Force Manual in a contractor-owned contractor-operated facility. We have the same program in several areas. If they grant us a waiver across the street, but they say they can't grant us a waiver in our contractor-owned contractor-operated facility, that we have to have 100% compliance. So its legal for us to deviate across the road but its not legal for us to go ahead and non-comply on our own property. Does DCAS have a solution for this?

ACKERMAN: I think this is basically one of the reasons why we're trying to establish these ASPR clauses and ASPR supplements. Basically I believe that this problem should have been overcome in the first preaward of the contract and the deviation procedure accepted under terms to the contract award in accordance with the ASPR requirements of 1-109.

MOLLOY: They've set a precedent for five years of granting us a waiver, now all of a sudden they tell us they can't legally grant us a waiver, that we should go 100% compliance.

ACKERMAN: The AFPI clause 7-4048 has been interpreted by the legal people of the Air Force as not being a mandatory safety requirement on privately-owned privately-operated contractors. We hope to avoid this situation by the inclusion of the ASPR clauses within the future contracts.

MOLLOY: On this pre-contract award survey will they inspect the contractor-owned contractor-operated facilities with the same criteria they inspect the Government owned facilities?

ACKERMAN: Yes sir.

MOLLOY: Why can't they grant a waiver?

ACKERMAN: In effect that is what they will do if they follow the procedures of ASPR 1-109 prior to granting a contract.

MOLLOY: I see, thank you.

COL. KAIN: In regard to the last question, one of the problems DoD is now undergoing and its a big job, they're trying to standardize the procurement business. They're trying to standardize the Army, Navy, and Air Force, and its a very difficult job because each of the Services has, thru the years, come up with their own method of operation. And this is really what the ASPR committee is trying to do, to do away with peculiar regulations within the Services and attempt to eventually standardize it. Its very difficult but I really think that within the next two or three years it will be done. And of course from our point of view in Contract Administration where we administer the contract after the contractor gets it, if all contracts are standardized, it makes our job ten times simpler.

UNIDENTIFIED: Why and how do they suddenly decide that at the contractor-owned and contractor-operated facility they can't legally enforce the requirements for siting, waivers, and exemptions; what's behind it, for years they could grant waivers, now all of a sudden they can't. Is there anyone here that could answer that?

KAIN: Is there anyone here from the Air Force that can answer that?

JEZEK: I don't know about the Air Force but I can tell you something that happened to the Army. We had a contract in a plant in Tennessee where two ladies were injured, they sued the Government for something like $800,000. They claimed that the Army was responsible for the safety at this particular plant, that the Army had taken over the quality assurance people or the safety people as far as they were concerned, and they sued the Government in Memphis, Tennessee. However, the Government won that case and that perhaps is why the Air Force got wise and said nix.

KAIN: You say the Government won that case?

JEZEK: The Government won that case, yes. I don't think the Army ever granted waivers to a PO-PO plant. I'm talking from the Army's standpoint only.

MILLER, OLIN-MATHIESON: When you put these manuals out, are you going to put them out thru the Government Printing Office so that they become available to us on purchase besides sending them out to us regular. Because I've found in the past, that those that I can purchase, I can obtain, whereas manuals that are not put out thru the Government Printing Office are practically impossible to obtain. Also it would be appreciated that those of us that are in the secondary contract business would be notified when manuals come out because we find that there is sometimes a considerable time lag like a year or more before we even discover that new manuals exist.

ACKERMAN: We considered this situation before we went to writing the manual. As far as we're concerned the ASPR supplements will be available thru the Government Printing Office. The determination of whether these are current is your responsibility, gentlemen. I can't come and tell you that we have a new manual. There will be a distribution list from the GPO and you should check the dates of your manual or supplement that you have available in your library to the ones that are published by the GPO. I think this is the only reasonable way we can ever contact everybody. We will have some sort of a bulletin notice to our people when new publications or revisions to publications are prepared and issued. Perhaps this will lso assist you in obtaining the latest data. But definitely you will be able to buy the proposed ASPR supplements. The reason we've made them supplements is due to the economic considerations and assuring availability to the public.

CAMP, AMC: Col. Kain mentioned that its intended to standardize the contracts in contract administration. Is it the intent of DOD to eventually administer all Government contracts in privately-owned privately-operated plants?

KAIN: I can't really answer that question. The DSA organization took over the administration number-wise of probably 95 or 99% of the facilities by number, dollar-wise, its probably closer to roughly 50%. There's really no answer to it right now. I don't think anybody knows. At the time that DSA took over these facilities the Military Departments wished to retain the large system type contractors and DOD granted them this privilege of keeping them. We don't know if this will eventually change or not. I can't answer that. I'm not sure anybody can.

BISHOFF, AMC: I'd like to express the Army Materiel Command's viewpoint on safety manuals and where and when you apply what safety

manuals. First of all there are three types of organizations. One is the Government-owned and Government-operated. Within the Army Materiel Command the Government-owned Government-operated installations must follow all the mandatory safety requirements in the AMC Safety Manual. If they cannot meet them, then the Army Materiel Command installation requests a waiver from Hq AMC. The second category is the Government-owned contractor-operated plant. Within AMC there is a mutual agreement between the contractor and AMC as to which of the mandatory safety regulations in the AMC safety manual must be followed. After that first mutual agreement, if there must be changes in operations which would violate a mandatory safety requirement, then the contractor thru the plant CO and thru the AMC echelons, request the specific waiver of the mandatory safety requirement. The third category is the contractor-owned and contractor-operated installation. Within AMC our feeling is this. We never give you a waiver of a mandatory safety requirement. When the pre-award survey is made the decision is reached as to whether or not you safely can produce the item which we need. If you cannot, then we ask you to make modifications to your plant. But once the contract is signed then we accept the plant the way it was when the contract was signed but we grant no waivers to you. I'm not sure how this is going to work in the future, Hy, maybe you would like to expound on the DCAS concept at the PO-PO plant because I think this is what is confusing people. It may have been that the Air Force has been granting waivers to contractor-owned contractor-operated plants, the Army has not. But in the future the Army hopes to continue the policy of no waivers to contractor-owned contractor-operated because the policy is as Mr. Jezek indicated to you and I think, as Mr. Ackerman also indicated, that at your own plant you are responsible for safety. And nothing that the DOD does should be construed as meaning that we are taking over the safety responsibility or sharing it with you. We will do everything we can to help you run a safe operation but in the final analysis and in the legal analysis, the private contractor is wholly responsible for safety.

ACKERMAN: Thank you Fred. This is exactly the position we have taken gentlemen. There is no question in our mind that we are not going to control your safety program or run the safety program for you. We feel that this belongs to you, you should have an appropriate organization with qualified personnel to help management within your plants to do the job properly, to give us uninterrupted flow of material, to protect your personnel as well as Government personnel in those plants and to insure that you protect the public in the immediate vicinity of your plants. Basically the procedures will be included in the ASPR supplement for safety. How you arrive at obtaining this type of requirement is your business. I recognize that this is always difficult. Your plants have never been designed completely for one product or two products. A pickle manufacturer might be a propellant manufacturer tomorrow. I don't know. But the case within Government-owned Government-controlled plants, is that all site plans, operational

plans for the flow of the material are reviewed and approved. This is not always the case with privately-owned privately-operated plants. So basically we have a fallacy to begin with. We're working on a premise that all safety has been included in design and that safety requirements exist. This is not always the case as Mr. Bishoff indicated. We are going to try to let you operate based upon an evaluation of the risk factors, the construction of your facilities, the inherent hazards that exist, and based upon your capability to produce the item safely and efficiently you may get the contract.

HAYDEN, THIOKOL: Would you repeat that part about AFPI 7-4048 as not being a legal clause in the contract?

ACKERMAN: Mr. Hayden, I would rather refer you to the Air Force representative here, Mr. Mann. But basically the AFPI clause as I have been told reads that the contractor shall comply with the intent of these manuals. I'd like Mr. Mann to correct me if my interpretation is incorrect, and based upon that consideration, the legal people within AFSC and the Air Force have determined that this is not a mandatory requirement on privately-owned privately-operated plants.

HAYDEN: My question pertains basically to this AFPI 7-4048 clause because this is the clause that calls out all the manual requirements.

ACKERMAN: That is correct.

HAYDEN: Are you saying then that we read the intent and not the mandatory requirements?

ACKERMAN: Again, I'd rather refer you to Mr. Mann, I can't make that decision for the Air Force.

STONE, LOCKHEED: All I want to do is say Godspeed to you. I hope to heck that you get it done because I think it will help all of us tremendously if we have one manual to follow in a plant where we have 3 or 4 different contracts. Thank you.

MOLLOY: I'm not addressing this remark to you Mr. Ackerman, but I would like someone from the Air Force to tell me - when you have a contract, how you can substantially comply because at our contracting offices, you either comply or you don't comply and they gave us a choice. In our contract we have the manual 127-100 which says we are to request a waiver if we can't comply. So we requested a waiver, then they told us they can't legally enforce it. Now we're trying to get to the middle of this road substantially complying. Is there anyone here who can tell me how you substantially comply, do you or don't you comply?

PERKINS: May I suggest that we appear to be hearing discussions that are somewhat outside of the assigned mission of the Seminar and we have exhausted the time allotted for this subject. Perhaps it would be wise if you fellows would get together informally outside of the session.

COL. Kain: Thank you very much gentlemen.

VARIATION OF SOUND INTENSITY WITH TIME

Mr. Beauregard Perkins
Consultant to Ballistic Research Laboratories
Aberdeen Proving Ground, Md.

The discussion that I am about to present was stimulated by the concern expressed by some workers in the field of sound intensity and air blast damage, over the variation of overpressures measured by various groups under apparently identical conditions. The burden of the presentation will be to show that variation is to be expected rather than to cause wonder or to raise doubts. All the facts to be discussed are part of the mental inventory of everyone here although perhaps in some cases certain facts have become dust covered due to concentration of the individual on other phases of the subject of sound propagation.

The major variations of the measured overpressures occur in the low pressure region. Of chief concern to us is the region from 0.1 to .0001 psi on the Pressure vs Distance curve in a uniform atmosphere since a slight focussing will raise these values to levels reported to cause damage by air blast from explosions or from sonic booms. The sound level observed at a given point are normally assumed to depend on:

1. Sound level at the source (Magnitude of Explosion);
2. Distance from source to point of observation;
3. Velocity structure of air mass between source and point of observation (Pattern of Wave Paths).

In addition, consideration should be given to the number of velocity discontinuities crossed by the sound wave in traveling from the source to the observation point. The reason for the presence of these discontinuities will now be discussed.

In the calculation of wave paths the air mass between the sound source and the point of observation is assumed to be layered in such manner that the velocity of sound varies with altitude, but at any given altitude the sound velocity is uniform to a distance of 30 or 40 miles. This last assumption is a very severe demand on nature and is very unrealistic. Heated terrain, small lakes, densely foliaged areas or scattered clouds affect the temperature of the contiguous air. A slight breeze will distribute small air masses of differing temperature or relative humidity between the source and the observation point and frequently vortices occur varying in size from 10 cm to 10 Km in diameter. Due to instrumentation difficulties I do not have firm values for temperature variation with time, but just before leaving for this meeting I received a copy of preliminary data from the Ballistic Research Laboratories at Aberdeen Proving Ground. The thermometer used has a relatively long response time and the

the altitude was only 40 feet but the measurements were sufficient to indicate fluctuations of 2 to 4 degrees Centigrade over periods of 1 to 3 minutes. Measurements are planned at altitudes of about 500 feet and 1000 feet using a thermometer having a shorter response time. The sound wave being propagated thru the atmosphere will be passing from a mass of air of one acoustic impedance to another having a different acoustic impedance. When this occurs some of the acoustic energy will be reflected and some transmitted. (The acoustic impedance is the product of the sound velocity and the density of the medium.) Several interfaces where the acoustic impedance changes abruptly may be present along the path and at each interface some of the wave energy will be reflected and some transmitted. The transmitted energy will be refracted through the new mass of air or diffracted around it thus changing the direction of propagation of the sound wave. Both the reflection of the wave and the change in direction of the transmitted wave will affect the amount of energy reaching a given position.

The wind at a given altitude will vary both in speed and direction with time. Anyone that has flown a kite has seen evidence of this. A calculated pattern of paths based on high velocity components at a few altitudes will be different from one based on low velocities at those same altitudes. Table 1 gives two sets of Velocities vs Altitude used in computing the ray patterns of Figure 1. The velocities at only two altitudes vary and then only by 5 ft/sec and 8 ft/sec yet the patterns are quite different. If the velocities at higher altitudes had differed the variation in the ray patterns would have been more striking.

For practical reasons the soundings to determine the velocity profiles are limited in both time and space. Meteorological stations are expensive and generally limited to one for each area where explosives are detonated and the soundings are seldom less than four hours apart. Stations at short intervals in all directions from the sound source would help to provide an average condition in any given direction. However, since the variation of the various parameters with time are such that the velocity of sound may vary several feet per second in a few minutes it is not possible to determine the precise conditions prevailing except at the time of the meteorological sounding.

The measurements of sound level which have been made were made under the capricious conditions just discussed. From my experience I feel that under apparently identical conditions a variation of one order of magnitude (10 to 1) should be expected. Thus the pressure to be expected under a given combination of sound velocity gradients in the atmosphere should be represented by a range of values rather than by a single point.

If the primary concern of the individual controlling the firing is public relations, it is obvious that the maximum possible sound level at the critical area should be used to determine whether or not firing should be permitted.

If, however, the primary concern is the conclusion of tests or the completion of an investigation, then the cost of possible damage must be weighed against the cost of postponement (reassembly of materials and personnel) or against the hazard of maintaining the accumulated HE for several days.

VELOCITY vs. ALTITUDE FOR TWO CASES

ALTITUDE (FEET)	CASE 1 VELOCITY (FT/SEC)	CASE 2 VELOCITY (FT/SEC)
0	1120	1120
1000	1122	1117
2000	1124	1116
3000	1128	1128
4000	1133	1133
5000	1140	1140
6000	1143	1143
7000	1140	1140
8000	1135	1135

Table 1

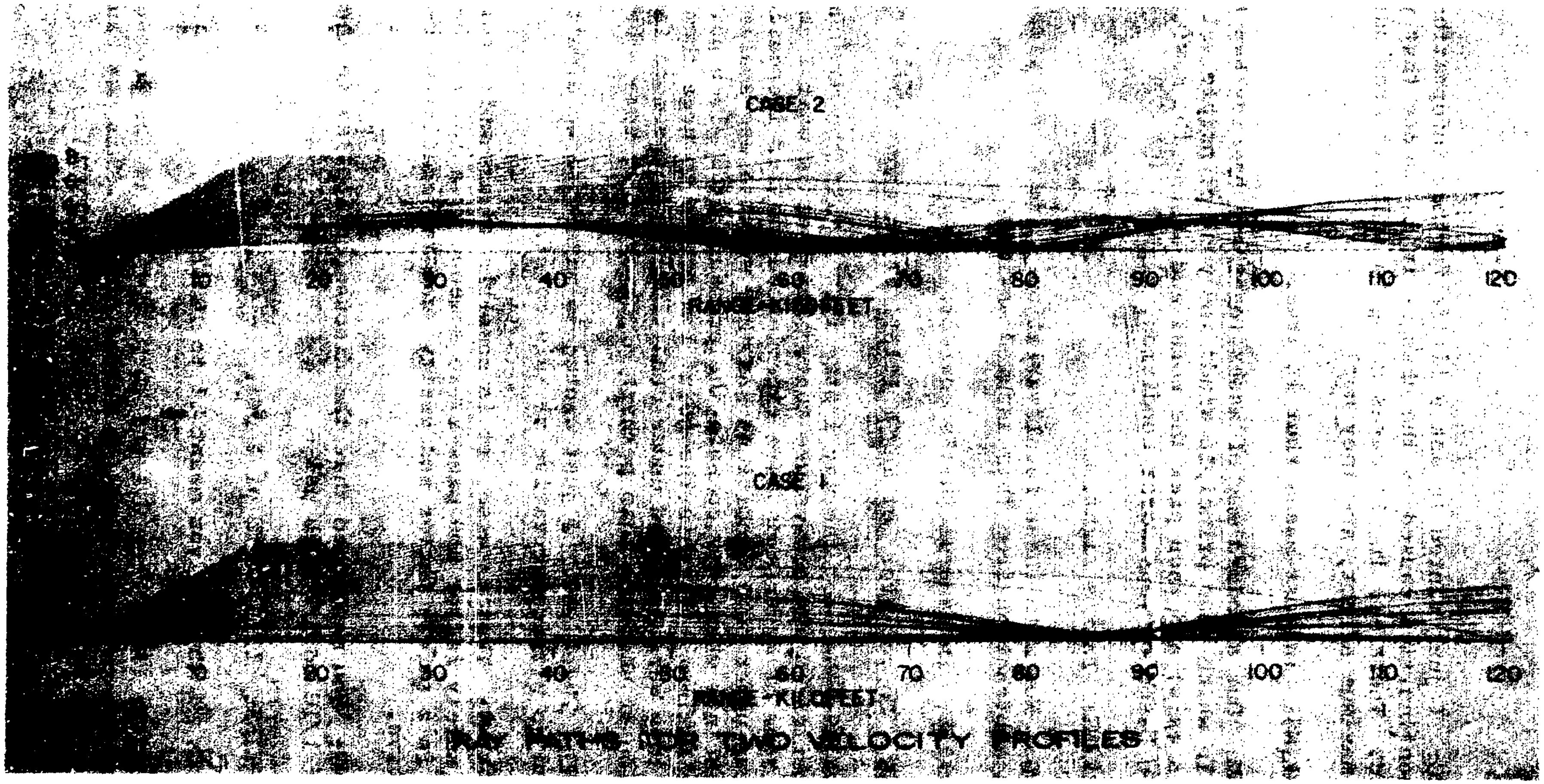
CASE 2
10 20 30 40 50 60 70 80 90 100 110 120
CASE 1
10 20 30 40 50 60 70 80 90 100 110 120
VELOCITY PROFILES

Figure 1.

KING: I just wanted to ask a little further information about the discontinuities caused by the changes in impedence that you mentioned. These are in all cases going to subtract from our total assumed maximum affect, are they not?

PERKINS: In most cases that is true.

KING: Our standard way of assessing these hazards has been to pick vectors in which your principle winds and your principle velocity gradients exist and then pick the worst and assume the maximum multiplication based on your worst condition, right?

PERKINS: That's right.

KING: Now with these local variations, are we not always going to get a subtraction from this assumed maximum?

PERKINS: In general that's correct.

KING: Do you ever get any multiplication above this?

PERKINS: No, not the way I play it. I take the maximum that I've ever experienced and always use that. But that is what I am discussing because some of my friends have experienced smaller increases in pressure at a focus under some conditions and they want to use smaller multiplication factors when they compute the pressure at a given point, rather than the maximum. That is the point I'm trying to urge them not to use because they were measured under conditions that are more favorable for permission of shooting than perhaps might exist at some other time.

KING: Thank you. I just wanted to make sure we didn't go overboard and go ultraconservative at this point.

PERKINS: That is wise, it is possible to assemble criteria and apply a safety factor and pass it to someone at a lower echelon and he puts in a safety factor and pretty soon the conditions become prohibitive.

KING: You mentioned that the discussion applies in the pressure range of 1/10 to 1/1000th psi -

PERKINS: 1/10,000th of a psi.

KING: I thought you meant .1 to .001?

PERKINS: No. From 0.1 psi to 0.0001 psi is the pressure range in which some pressure-distance curves differ. This has caused some

workers to feel that my maximum multiplication factor is too large. If I am in error I am erring on the safe side.

KING: I'd like to rephrase my question. I think you mentioned the range that we're concerned about these acoustic problems is in the area of .1 to .001 psi because we assume a multiple of 100 as a maximum.

PERKINS: Yes.

KING: Does this sort of relationship, this local discontinuity, have an equal effect when you get your higher pressures or does it have a worse effect?

PERKINS: Higher pressures from the <u>same</u> <u>source</u> would be much nearer the source and the path of the sound would not reach as high into the atmosphere as the paths to more distant points; therefore, there would be less opportunity for temperature and wind variation to affect the energy propagated than in the case where the propagation is to a greater distance, that is, to a point where the overpressure is lower. However, if the high and low pressures are being considered at the same distance from the source then the effect of changes in wind and temperature should be the same for high or low overpressures.

SEWARD, NASA: I was wondering if there was any criteria for claim purposes which would indicate the minimum acceptable acceleration to structures that could be applied.

PERKINS: When you speak of accelerations are you talking about ground shock or air blast?

SEWARD: I'm talking about acoustical induced vibrations to structures.

PERKINS: This is one of the things I'm envious about these boys who have been experimenting close-in. We have yet to get a good criterion for damage, whether its impulse or pressure. As far as ground shock is concerned, its been pretty well tied down by the Bureau of Mines as due to the particle velocity and I would like to tie down damage to a structure from air blast to some parameter such as pressure or impulse and also study resonance effect. But I haven't been able to.

SEWARD: I'd like an appreciation in this focusing effect, for how much ground area is affected by this. We've recently had a legal complaint from a home owner yet several feet away there were no complaints. So is this energy very directive?

PERKINS: Not to that extent. But I'll say one thing, there's a very popular belief that anything the Government pays for costs nothing to anyone. In many claims that comes in and I've reviewed a lot of them, folks have put in claims for some very absurd things. When I've made a mistake of discussing some of these things with individuals, I have been asked "why was I so interested in keeping the Government from paying for their plastered walls, it wasn't going to cost me anything, it wasn't going to cost anybody anything, the Government was going to pay for it." Folks will use that philosophy in putting in claims when all they've heard was the sound of an explosion. They're not all crooked but there is sufficient to justify a constant and critical surveillance. I do not have a firm measurement of the width of a focus area but its something on the order of one mile in width in most cases. It might extend out to 2 miles under some conditions, I don't know. But I use two miles as an outside limit when a claim comes in to be evaluated as to whether or not it is reasonable because of the possibility of the focus position and although it may not be two miles in width, it can shift a mile along the ground as a result of variations in velocity.

HIGH ENERGY PROPELLANT PROCESSING SAFETY

by

E. A. Platt*

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ABSTRACT

Thiokol Chemical Corporation maintains a continuous safety test program to define hazards associated with the research, development, and manufacture of high energy propellants. Studies have been performed to improve safety in handling, manufacturing, storing, and shipping of the raw materials, intermediate compositions, and final propellant compositions. Materials involved in these studies include:

1. Ammonium perchlorate oxidizer,
2. A Thiokol developed high energy oxidizer,
3. Combinations of propellant raw materials,
4. Uncured and cured propellants.

A series of standard safety tests is normally used to initiate a safety study. In most programs, the standard test data are supplemented with results from special tests designed to simulate actual process conditions.

Studies supporting propellant manufacture included mixer hazards from initial phases through cleanup, cutback, and finishing operations. In addition to these studies, standard military explosives hazard classification tests and inhouse explosive properties studies were conducted to determine critical diameters, minimum booster, card gap, and projectile impact values.

The results of these studies were used as guidelines in the preparation of operating procedures for all phases of rocket propellant development and manufacture. Numerous operating line equipment changes were made to reduce the hazards indicated by the test results. Because of this work, Thiokol has one of the better safety records in the solid propellant industry. The purpose of this paper is to summarize these safety programs.

*Chief, Explosives Development and Evaluation Unit

INTRODUCTION

In any manufacturing operation, safety is a primary concern, particularly when the operation involves highly flammable or explosive materials. One method of assuring personnel safety is to perform all operations remotely. This approach, however, may be prohibitively expensive and it will not protect facilities and equipment.

The degree of hazard in any explosive operation varies throughout the operation. Therefore, since people must be present at some time in the operation, a second approach to providing personnel safety is to use remote control during the hazardous stages of the operation. The hazards of the materials involved and of the process must be understood if this method is to be used.

Thiokol Chemical Corporation's Wasatch Division is currently involved in development and manufacture of solid propellants and rocket motors. All phases of propellant processing safety are evaluated to eliminate or reduce fire and explosive hazards.

Safety evaluations are performed by using relative or direct application testing. The relative method involves comparison of data from the subject material with an established standard. This method is adequate when:

1. The test results for the subject material demonstrate lower sensitivity than the standard.
2. Large scale production and handling of the standard material has a proven processing safety record.
3. The manufacturing processes for the standard and the material under study are identical.

One direct application method for safety evaluations involves testing under simulated process conditions. This technique requires an extremely large amount of testing, because of the wide variety of processing conditions.

Thiokol uses both relative and direct safety evaluation methods. Initially, materials are tested for relative sensitivity and compared to a standard material. The subject material is considered safe if it tests equal to or less sensitive than the standard and the processes are equivalent. However, if a hazard is indicated by the relative tests, additional testing under simulated process conditions is conducted to more closely define the hazards.

The majority of the work discussed in this paper involves composite solid propellants. However, the methods used and much of the data are applicable to any type of solid rocket fuel. It should be noted that the safety work conducted at Thiokol is extremely voluminous and this paper simply highlights parts of the total program.

HAZARDS EVALUATION PROCEDURE

LITERATURE SEARCH

The first step in conducting hazards evaluation is to screen sources to determine available information on toxicity, flammability, stability, and recommended storage and disposal procedures. The accumulated data are distributed to all interested personnel.

COMPATIBILITY TESTS

Upon completion of the literature search, the compatibility of the new ingredient with other propellant constituents is determined. Small 2 gm hand mixes are stored for 48 hr at 70°C (158°F) and at room temperature. If any of the samples char, explode, ignite, or produce gassing, the ingredient is rejected for use in the proposed propellant composition.

HAZARDS CLASSIFICATION (THIOKOL)

After demonstrating ingredient compatibility, the propellant is manufactured in a 1 pt vertical mixer to provide sufficient samples for conducting the standard hazards classification tests. These tests consist of:

1. Thermal stability,
2. Impact sensitivity,
3. Friction sensitivity,
4. Electrostatic sensitivity,
5. Detonation susceptibility,
6. Deflagration to detonation transition.

The deflagration to detonation transition test is performed only when detonation occurs in the detonation susceptibility test.

Prior to conducting the hazards classification test series, a review of the propellant composition and proposed mix and handling procedures is conducted to determine the materials that need to be evaluated. The test materials consist of:

1. Any new ingredient considered to be explosive or highly flammable.

2. Intermediate products that might be present during any part of the manufacturing cycle.

3. Uncured propellant.

The propellant is assigned a Thiokol hazard classification, which is dependent on the material test results. The classification categories and the respective test levels for each category are presented in Table I. Type A materials are considered to be relatively safe for processing by normal procedures. Type B materials are more hazardous than Type A. However, Type B materials are considered processible when proper safety precautions are observed. The operating procedures are reviewed, and in many cases, additional safety testing is conducted to more closely define the hazards of Type B materials. "Red Line" materials are considered too hazardous to use except where the degree of hazard is completely defined and special processing equipment and procedures have been developed to insure safety to personnel and property.

The safety test levels under Type A materials in Table I are based on results from materials that have been safely manufactured in large quantities at Thiokol's Wasatch Division. Any new material showing sensitivity equal or lower than the Type A levels is considered safe to process by conventional methods. The test levels listed under the "Red Line" category are based on results from materials known to be extremely hazardous to process with existing equipment and procedures. The Type B category falls between these two extremes. Thiokol experience with materials in the B category has been limited primarily to experimental propellants.

MILITARY AND ICC HAZARDS CLASSIFICATION

After the propellant has been manufactured and cured, the military and Interstate Commerce Commission (ICC) hazards classification tests are conducted. These tests measure the hazards involved in shipping, handling, and storing the propellant and propellant loaded rocket motors. These tests are described in the ICC Explosives Transportation Regulation, Tariff No. 15 and DOD Document TAGO 5617-A. Flammable or explosive propellant ingredients are also subjected to these tests prior to being transported in interstate commerce.

DISCUSSION

PROPELLANT CONSTITUENTS

The only single explosive ingredient used in most composite propellants is the oxidizer. The majority of the experience at Thiokol's Wasatch Division has been with ammonium perchlorate (AP) oxidizer, although a significant amount of work has been done with hydrazinium diperchlorate (HP_2), a high energy experimental oxidizer. Several other ingredients, such as certain burning rate catalysts, create a hazardous condition, but only when mixed with other materials.

TABLE I

THIOKOL HAZARD CLASSIFICATION CATEGORIES

Test	Categories		
	Type A	Type B	Red Line
Thermal Stability	⩾24 hr at 149°C (300°F)	<24 hr at 149°C (300°F)	<24 hr at 107°C (225°F)
Impact Sensitivity (in.)	⩾11	<11	<4
Friction Sensitivity (lb)	⩾64	<64	<10
Electrostatic Sensitivity (joules)	⩾8	<8	<0.06
Detonation Susceptibility	Does not Detonate	Detonates	--
Deflagration to Detonation Transition	--	Does not Detonate	Detonates

Thiokol purchases AP in nominal particle sizes from 200 to 400 microns. A portion of the oxidizer is then ground before being used in propellant. The as received AP was assigned a military classification of 12 on 28 August 1962. However, this classification does not apply to smaller particle size materials such as that ground for MINUTEMAN Stage I propellant. HP_2 is a relatively new experimental oxidizer which was developed, and is now being manufactured, at Thiokol's Wasatch Division.

<u>Thiokol Standard Safety Tests</u>

The Thiokol standard safety tests were conducted on both oxidizers listed above. The results, presented in Table II, indicate no significant differences among the different particle size AP samples tested. AP is thermally stable and not particularly sensitive to impact, friction, or electrostatic environments. All AP samples tested were detonable; however, they would not transit from deflagration to detonation.

HP_2 oxidizer is significantly less stable than AP and is more sensitive to impact and friction. In addition, HP_2 is detonable and will readily transit from deflagration to detonation.

<u>ICC Explosive Classification Tests</u>

ICC Explosive Classification tests were conducted on small particle size AP and HP_2. Five different samples of AP and two samples of HP2 were tested for the environments specified in the ICC Explosives Transportation Regulations, Tariff No. 15. The AP samples consisted of three special samples from American Potash and Chemical Corp (AMPOT), one sample of standard MINUTEMAN ground, and one sample of Thiokol bag dust. The bag dust is extremely fine reject material obtained from the grinding operation. The particle size distribution analysis from these five materials showed a weight mean diameter range from 7.7 to 62 microns. The HP_2 samples consisted of dry HP_2 and a slurry of weak perchloric acid and HP_2. The classifications based on results from this test series are represented in Table III.

The ICC explosive classification evaluation of AP included tests for detonation shock sensitivity, fire sensitivity, and impact sensitivity. The smaller particle size AP samples, 8.5 μ and 7.7 μ, detonated when subjected to the detonation shock test. These samples also ignited more than 50 percent of the time when subjected to an impact drop test from a height of 10 in., but less than 50 percent of the time from a drop height of 3.75 inches. The larger particle size materials, 48 and 62 μ and 12 μ, did not detonate when subjected to the detonation shock tests. Fire test results on all five materials were negative. These test results indicate that the breakpoint between ICC Class A-3 and oxidizing materials is between 8.5 and 12.1 μ AP.

The ICC explosive classification evaluation of HP_2 included tests for detonation shock sensitivity, fire sensitivity, impact sensitivity, and thermal stability. The results from tests in all four environments of HP_2 slurry were negative. However,

TABLE II

THIOKOL STANDARD SAFETY TEST RESULTS

Test	AP (400μ)	AP (200μ)	AP (12μ)	AP (7.7μ)	HP_2
Thermal Stability (hr)					
at 300°F	>24	>24	>24	>24	--
at 275°F	>24	>24	>24	>24	4
at 225°F	>24	>24	>24	>24	>24
Impact Sensitivity (in.)	35	46	32	31	21
Friction Sensitivity (lb)	>70	69	>70	>70	24
Electrostatic Sensitivity (joules)	>8	>8	>8	>8	>8
Detonation Susceptibility	Det	Det	Det	Det	Det
Deflagration to Detonation Transition	No Det	No Det	No Det	No Det	Det

TABLE III

ICC EXPLOSIVE HAZARD CLASSIFICATIONS

Material	ICC Explosives Hazard Classification
7.7 μ AP	Class A, Type 3
8.5 μ AP	Class A, Type 3
12 μ AP	Oxidizing Material
48 μ AP	Oxidizing Material
62 μ AP	Oxidizing Material
HP_2 Slurry	Class B
Dry HP_2	Class A, Type 4

dry HP_2 detonated during the detonation shock and fire tests, and ignited 50 percent of the time from an impact of 4 inches. No reaction was observed during the thermal stability test.

TAGO 5617-A Explosive Classification Tests

The second series of tests was conducted in accordance with the criteria of Phase II, DOD Document TAGO 5617-A. This series included card gap, exposure to fire, and bullet impact test.

Seven AP samples were evaluated to determine card gap values. The seven samples included the five materials used in the previous series plus as received and special coarse material having nominal particle sizes of 200 and 400μ respectively. All seven of the AP materials demonstrated card gap values greater than 70 cards and, therefore, are classified as military Class 7 explosives in accordance with the DOD criteria. Aluminum, rather than the recommended mild steel, was used as the witness plate material for the card gap tests. This was necessary because the pressure from detonating AP, in small diameter charges, is too low to penetrate a steel plate.

For the fire exposure tests, 10 in. long by 5 in. dia Schedule 40 pipe was used rather than the 5 in. dia motor required by DOD Document TAGO 5617-A. A 0.5 in. thick steel plate was welded to one end of the pipe. The other end was sealed with a pipe cap after insertion of the AP. This confinement induced a high pressure that would enhance any transition from burning to detonation. Only the 7.7 and 12μ samples were tested. No detonations occurred in either of the tests.

The test container used for the bullet impact tests was the same as that used in the fire tests. Again only the 7.7 and 12μ samples were tested. A 30 cal armor-piercing bullet was fired into the side of each container from a distance of 50 feet. The bullet penetrated the container and ignited the AP; however, no detonation was observed.

All AP materials tested appeared to be sensitive to shock, as evidenced by the results of the card gap tests. However, the materials apparently do not transit easily from burning to detonation, since no detonations occurred in either the fire exposure or the 30 cal bullet impact test.

Thiokol Special Safety Tests

This test series was conducted to define actual oxidizer processing hazards. The tests were designed to simulate actual process conditions or potential conditions.

Fire Exposure on AP--The fire exposure tests were conducted in actual shipping and storage containers designed to offer maximum confinement. The test objective was to determine if the container material (aluminum) would provide sufficient fuel to induce transition from burning to detonation. AP samples of 7.7 and 12μ were tested. The sample sizes were 411 and 416 lb respectively.

Internal pressure ruptured the containers during both tests. The AP burned but did not detonate. The seismic monitors recorded ground shocks during both tests equivalent to detonation of less than 1lb of ground AP. Again the test results showed that these types of AP materials, even while burning and in the presence of aluminum fuel, will not readily transit from burning to detonation.

Bullet Impact on AP--A 35 gal. steel drum containing 159 lb of 12μ AP was subjected to an impact from a 30 cal armor-piercing bullet and later to several impacts from 50 cal armor-piercing bullets. The 50 cal bullets passed completely through the drum and AP. The 30 cal bullet did not pass completely through the drum. There was no noticeable reaction to the 30 cal bullet and no resulting fire. In the test in which several 50 cal bullets were fired into the drum, the AP ignited and approximately two thirds of the material was consumed.

Initiation Tests on AP Dust--Initiation tests were conducted on air dispersion of 7.7 and 12μ AP to determine if this material presented an explosive hazard and if so, what energies were required to initiate the reaction. The testing was intended to duplicate environments occurring in AP systems in which AP dust is collected or air conveyed. The most probable initiating source in this processing operation is electrostatic discharge. However, blasting caps and pentolite boosters were used, since they impart more energy than electrostatic spark.

The AP dust was dispersed by air jet into the bottom of a steel pipe and the initiator positioned at the top of the pipe. Two tests were conducted on each AP sample. No. 8 blasting caps were used as initiators in the first test and 1 by 1 in. 50/50 pentolite boosters were used in the second test. Neither the blasting caps nor the pentolite boosters initiated a sustained detonation, as evidenced by the AP dust remaining after the test. Some AP dust reacted around the initiators, but not in sufficient quantity to distort the pipe.

Large Scale Electrostatic and Drop Tests on HP_2--Large scale impact and electrostatic tests were conducted to simulate potential process conditions. No reaction was observed when 18 lb of HP_2 was subjected to an electrostatic spark of two joules. An energy of two joules is considered relatively high for any phase of HP_2 manufacturing. Because of the precautions taken (equipment grounding, conductive shoes, etc.), accidental ignition from electrostatic spark is considered unlikely.

Two 40 ft drop tests, involving relatively large amounts of HP_2, resulted in no reaction, although the test cans were damaged considerably from impact force. These results indicate that accidental droppings of HP_2 during handling processes would not constitute a safety hazard.

Long Term Storage Tests on HP_2--Because of the low thermal stability of HP_2, a series of tests was initiated to establish duration and temperature limits for safe storage. The results of tests conducted thus far are listed in Table IV. The results indicate that thoroughly dry HP_2 can be stored in relatively large quantities for an extended period of time at moderate temperatures. Storage in excess of one month at 165° F does not affect the dry material. However, wet cake HP_2 (HP_2 wet with perchloric acid) becomes a detonation hazard when stored at a temperature exceeding 130° F.

Because of the necessity to store both dry and wet cake HP_2, a storage area with the capability of maintaining moderate temperature was constructed. The material is stored underground in 25 to 50 lb lots. The temperature inside the storage container is continuously monitored.

Effect of Water Deluge--The low thermal stability of HP_2 dictates that any operation involving application of heat should be considered potentially hazardous. A relatively large amount of heat is applied in the oxidizer drying process to remove residual perchloric acid. As long as vacuum is maintained to remove acid vapors, the drying cycle is considered relatively safe. If vacuum is lost an extreme hazard is encountered. Because of this hazard, all drying is conducted by remote methods. Remote operations provide protection to personnel, but not to the processing equipment and facilities. Studies were therefore initiated to evaluate the effectiveness of water deluge on HP_2 burning. Test results are listed in Table V. An initial series of nine tests was conducted, using one lb samples with various deluge delay times and ignition locations. Burning HP_2 was extinguished in all cases. The tenth test was performed to determine if the same degree of effectiveness could be obtained with a relatively large sample (50 lb) conditioned to 170° F. However, the material detonated prematurely before the deluge mechanism could be activated. One thermocouple indicated a temperature of 115° F in the HP_2 prior to detonation. The heating element in the test container apparently created a hot spot in the HP_2, starting the decomposition reaction. A hot spot in the material would not be recorded by the monitoring equipment unless it was located close to the thermocouple. Confinement of the HP_2 in the test container would create a rapid transition to detonation. The final two tests conducted were similar to the tenth test except that no heating was attempted. Two different deluge delay times were tested and in both cases the fire was completely extinguished. Successful deluging operations have since been conducted on inprocess HP_2 heated in the dryer to 170° F.

Water deluge was exceptionally effective even after HP_2 had burned for 10 seconds. An immediate action taken as a result of this study was installation of two separate deluge systems in Thiokol's HP_2 drying facility. In one system, the water is routed directly into the drying chamber to allow deluge during drying. The second system employs a manually operated external nozzle directed toward the dryer opening, which can be actuated by the operator if decomposition is observed or suspected while the dryer is open. During the drying process the operator is instructed to immediately deluge if a loss of vacuum or an abnormal temperature

TABLE IV

LONG TERM STORAGE OF HP_2 OXIDIZER

Material Condition	Temperature (°F)	Sample Weight (lb)	Test Time (hr)	Result
Wet	150	35.5	36.0	Detonation
Wet	120	37.5	67.5	No Reaction
Wet	150	37.5	38.8	Detonation
Wet	130	24.0	18.8	No Reaction
Wet	150	24.0	15.1	Detonation
Dry	95	32.0	20,000*	No Reaction
Dry	165	32.5	935.1	No Reaction

*Test still in progress.

TABLE V

EFFECT OF WATER DELUGE

Test No.	Test Sample	Temperature (°F)	Sample Weight (lb)	Burning Time (sec)	Result
1	Wet Cake	Amb	1	0	Extinguished
2	Wet Cake	Amb	1	0	Extinguished
3	Wet Cake	Amb	1	5	Extinguished
4	Wet Cake	Amb	1	10	Extinguished
5	Dry HP_2	Amb	1	0	Extinguished
6	Dry HP_2	Amb	1	5	Extinguished
7	Dry HP_2	Amb	1	10	Extinguished
8*	Dry HP_2	Amb	1	0	Extinguished
9**	Dry HP_2	Amb	1	5	Extinguished
10	Wet Cake	170	50	***	Detonated
11	Wet Cake	Amb	50	2	Extinguished
12	Wet Cake	Amb	50	7	Extinguished

*Ignited at middle of sample.
**Ignited at bottom of sample.
***Detonated before reaching test temp. (Deluge not actuated.)

rise is experienced. The procedure insures deluging before decomposition can progress to a violent stage. The deluge system has been successfully used in this manner several times.

HP_2 Shipping Container--The ICC classifications for HP_2 listed in Table III presented problems, in that dry HP_2 could not be shipped, and in order to ship HP_2 in an acid wet condition, a vendor would need extraction and drying equipment. Studies were therefore initiated to establish methods for safely handling and transporting HP_2.

To overcome this problem a special shipping container was designed which is acceptable to the ICC for shipment of Class A Type 4 material. The container has been developed and proven safe. The ICC has issued a special shipping permit for transportation of dry HP_2 in the special container.

The design of the container consists of a wide mouth glass jar for containing the HP_2, overpacked with a standard steel drum. The space between the glass jar and the steel drum is filled with water. The container is constructed so the supports will break the glass jar if it is subjected to excessive shock, such as nearby explosions or drop impact. In addition, a special device is attached for breaking the jar when the container is exposed to fire or extreme heat. Breaking the glass jar allows the water from the outer container to deluge the HP_2, thus desensitizing the material.

To demonstrate the effectiveness of this container a series of safety tests was conducted including the following:

1. Sympathetic detonation,
2. 40 ft drop,
3. Fire exposure,
4. 30 cal bullet impact,
5. 50 cal bullet impact.

Six test containers, as shown in Figure 1, were fabricated. Two of the containers were used for the sympathetic detonation test. One container (the accepter) was filled with approximately 8 lb of HP_2 and the other (the donor) was filled with approximately 8 lb of AP and diesel fuel. The donor charge was initiated with a 2 in. dia by 2 in. long pentolite booster, which was initiated with a No. 8 blasting cap. To determine the violence of reaction in the HP_2, a lead plate-primacord witness was inserted about 3 in. into the HP_2. The two containers were set side by side for the test.

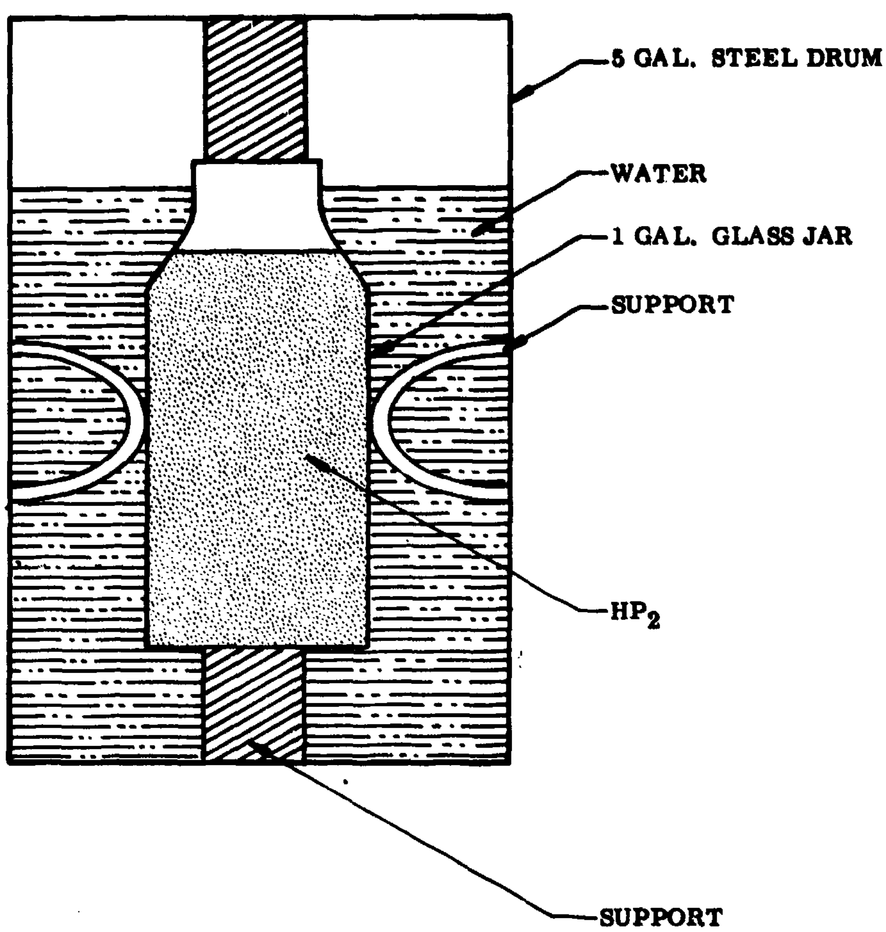


Figure 1. Apparatus for HP_2 Shipping Container Tests

The blast from the donor charge was a high order detonation. However, the HP_2 did not ignite. The HP_2 was completely dissolved in the water that had surrounded it prior to the test.

A third container was used for the 40 ft drop test. The container was filled with approximately 8 lb of dry HP_2 and dropped from 40 ft onto a concrete pad. No reaction of the HP_2 was observed.

The fourth container, used for the fire exposure test, was equipped with a device to break the glass jar when subjected to excessive heat (greater than 73°C). The container was filled with approximately 8 lb of dry HP_2 and subjected to open flame.

Thirty-nine minutes after ignition black smoke was observed coming from the top of the metal container. The lid had been ejected, apparently from steam pressure. Post-test inspection of the container revealed it to be dry with only fragments from the glass jar remaining.

The fifth and sixth containers were used for bullet impact tests. In the 30 cal test, the force of the bullet impacting the water ejected the drum lid and upset the drum. No reaction of the HP_2 was observed. The HP_2 was almost completely dissolved by the surrounding water.

The 50 cal bullet impact test resulted in detonating the HP_2. It should be noted, however, that the energy from the 50 cal bullet is nearly 5 times that of the 30 cal bullet.

After viewing these tests Dr. W. G. McKenna, chief chemist of the Bureau of Explosives, recommended to the Interstate Commerce Commission that a special shipping permit be issued allowing shipment of 20 lb lots of dry HP_2. The permit was issued as recommended with the stipulation that two additional tests be performed to check the operation of the automatic deluge device.

In the preliminary safety testing of the HP_2 shipping container the automatic deluge device protruded outside the drum. This condition is highly objectionable for a shipping container. The final design (Figure 2) will be tested successfully approximately 50 times including two full scale tests, thus satisfying the requirements for the special shipping permit. The design of the shipping container used in the latter tests and presently used for HP_2 shipments is shown in Figure 3.

INTERMEDIATE PRODUCTS

Numerous propellant intermediate compositions can create hazardous situations during manufacture of solid propellant. Often a mixture of two relatively insensitive materials is found to be extremely sensitive. As previously stated, the

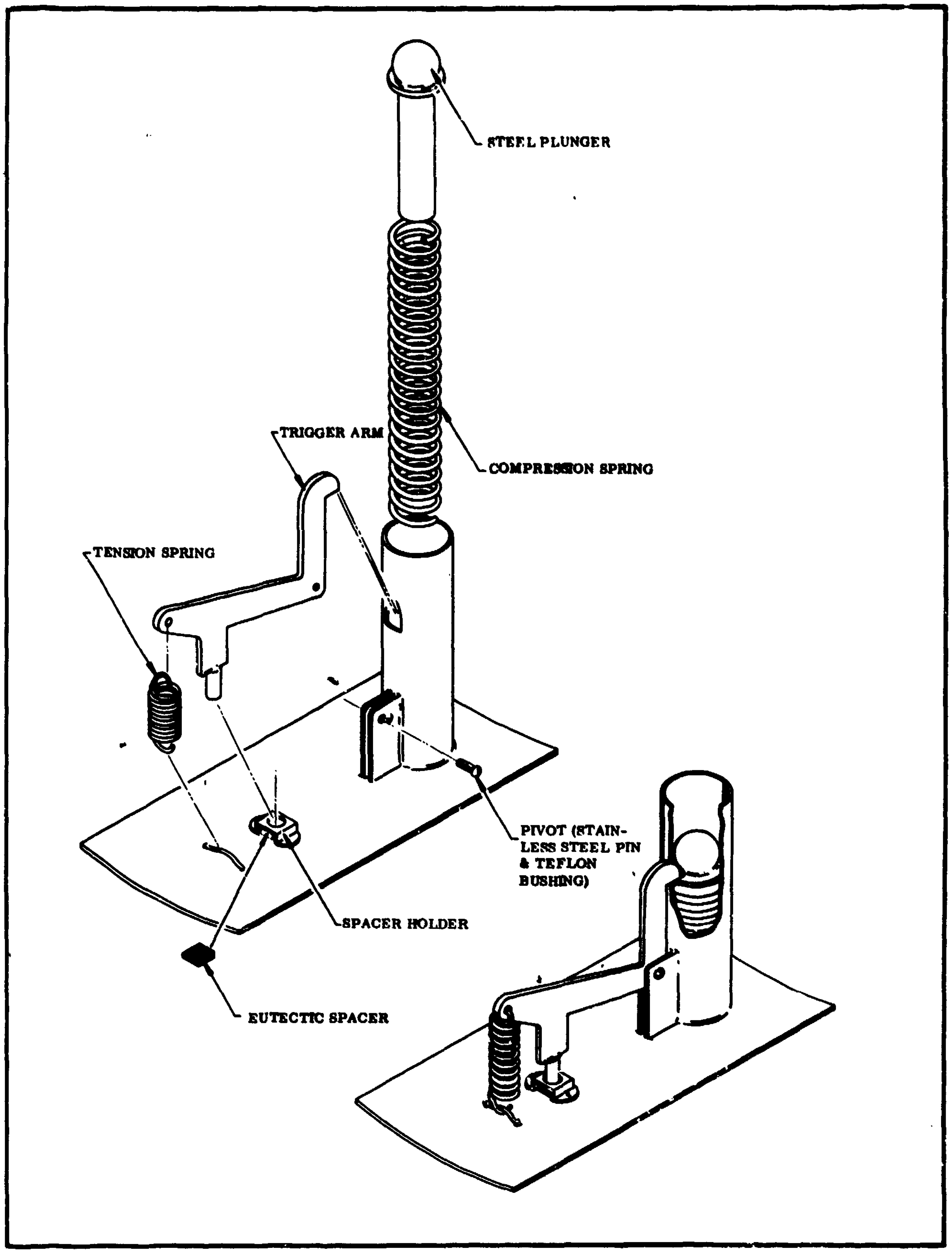


Figure 2. Automatic Deluge Device

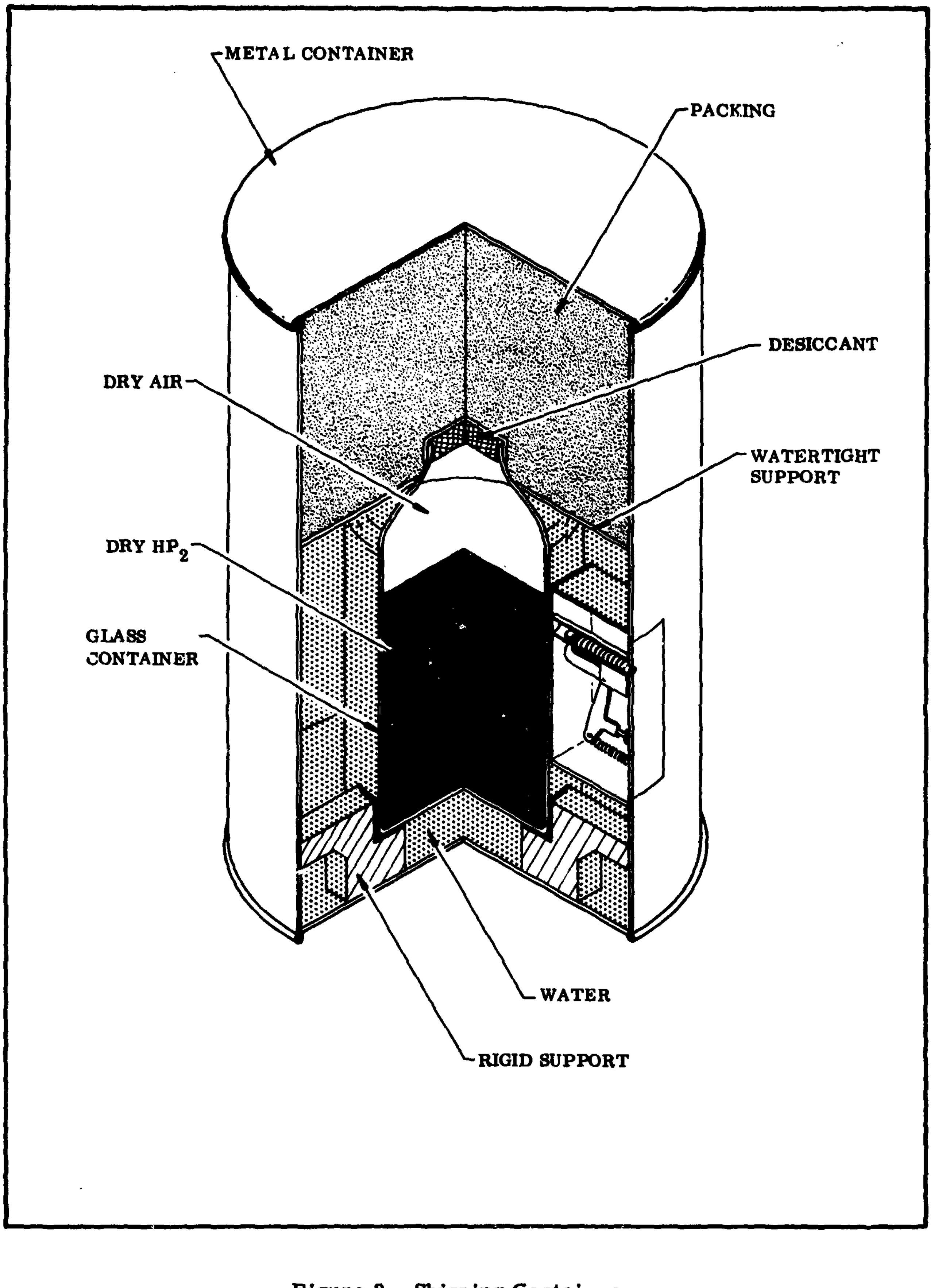


Figure 3. Shipping Container

Thiokol hazards evaluation procedure includes a review of these possible combinations and the proposed mixing and handling procedures to determine which materials require testing. This review and subsequent testing is conducted prior to manufacturing in mix sizes greater than 1 pint. The propellant system is also rechecked each time a change of ingredients or manufacturing procedure is proposed.

Oxidizer Premix Mixtures

The first step in normal composite propellant manufacture is to prepare a premix consisting of the binder, metal, fuel, and additives. This premix and the oxidizer are then blended together. In the early stages of mixing the ratio of oxidizer to premix can vary widely throughout the mix. A small portion of the incompletely mixed material is deposited on the mixer freeboard where it remains until it is manually scraped into the mix. Therefore these materials could be subjected to energies from the mixer blade or scraping tool.

Samples from each new propellant formulation, consisting of the premix with various ratios of AP, are tested. In all tests conducted to date, the sensitivity and stability data indicate the greatest hazard exists when the AP level is approximately equal to the level used in the propellant.

Curing Agent Rich Propellant

Since the curing agent is normally the last ingredient to be added to the propellant, curing agent rich propellant is present during early mixing. In addition, it is possible to have curing agent rich propellant or mixtures of curing agent and AP on the mixer freeboard until it is manually scraped into the mix.

Samples of curing agent and AP, plus curing agent rich propellant from each new formulation, are tested. All results obtained to date indicate a normal safety range for both material types.

Contaminated Oxidizer

During propellant processing, the oxidizer could become contaminated with a variety of materials. The contaminants could be:

1. Other propellant ingredients.

2. Equipment lubricants.

3. Residue from equipment.

4. Products from chemical reaction with equipment.

The methods by which the oxidizer can become contaminated are also numerous. Some possibilities follow.

1. Manual addition of the contaminant to the oxidizer.

2. Settling of airborne dry crystalline contaminant onto the oxidizer.

3. Splashing of liquid contaminant onto the oxidizer.

4. Addition of oxidizer to other, incompletely mixed, propellant ingredients.

5. Recrystallization of the contaminant onto the oxidizer after it has evaporated or sublimed.

6. Using materials of construction that are not compatible with oxidizer.

AP is compatible with most of the ingredients normally used in composite propellant and most of the materials of construction used for processing propellant. However, occasionally a material which creates a hazard when mixed with AP is found. HP_2 tends to be hazardous when mixed with contaminants, and the degree of hazard is greater than with AP.

<u>AP or HP_2 and Small Particle Al</u>--Mixtures of AP and small particle size Al are more sensitive to friction and electrostatic environments than either of the individual ingredients. Mixtures with the proper ratio of AP to Al are detonable and they will transit from deflagration to detonation. All friction and electrostatic tests conducted to date, however, indicate that the sensitivity of AP/Al mixtures is not critical.

The presence of AP/Al or HP_2/Al mixtures in the propellant process would create a significant hazard because of detonability. This potential hazard is eliminated by preventing the accumulation of a mixture. The Al is added to and completely mixed into a binder premix prior to addition of the oxidizer.

<u>AP/MAPO</u>--Tris (2 methyl aziridinyl) phosphine oxide (MAPO) is not compatible with AP. Some mixtures of AP and MAPO have autoignited at room temperature. Therefore, the presence of a mixture of AP and MAPO in the process would create a serious hazard.

This potential hazard is controlled by the same method used for the AP/Al mixtures discussed above. The MAPO is diluted to a safe level by adding it to the premix.

AP/Ferric Ferrocyanide--Mixtures of AP and ferric ferrocyanide are extremely sensitive to friction. The test result from a mixture of 70 percent AP and 30 percent ferric ferrocyanide was 6 lb. (See Table I for comparative values.) The friction sensitivity of 100 percent AP is >70 lb on the Thiokol tester. Again the potential is eliminated by adding the ferric ferrocyanide to the propellant premix.

AP/Ferrocene--Mixtures of AP and ferrocene are extremely sensitive to friction. Although these mixtures are less sensitive than AP and ferric ferrocyanide, they are considered extremely sensitive. The ferrocene is added to the propellant premix to reduce contact with AP, but ferrocene sublimes at normal mix temperatures and a small amount recrystallizes on the mixer freeboard. When AP is added to the mixer, some dusting occurs, resulting in some settling onto the ferrocene.

The friction hazard caused by the accumulation of AP and ferrocene on the mixer wall is controlled by removing the mixture with a dioctyl adipate (DOA) soaked cloth.

AP or HP_2/Petroleum Products--AP mixed with petroleum base oil is a well known explosive. The presence of this material in propellant processing areas would constitute a detonation hazard.

HP_2 mixed with petroleum base grease is the most sensitive material tested to date on the Thiokol friction tester. The material ignited consistently at the 1 lb level.

Mixtures of any petroleum base product and either of the above oxidizers are considered ignition and detonation hazards. These potential hazards are controlled by not using petroleum base products in propellant processing equipment. Fluorocarbon oils and grease are used to lubricate the equipment.

AP of HP_2/Copper Products--Under proper conditions the contact between AP or HP_2 and copper products will cause a chemical reaction, producing various copper perchlorate compounds. Most of these compounds are sensitive and sometimes detonable. Because of this potential hazard, the use of copper or copper alloys is forbidden in propellant processing areas.

UNCURED PROPELLANT

Thiokol's safety evaluation procedure requires that all propellant formulations be evaluated for hazards prior to manufacture in quantities greater than one pint. The Thiokol hazards classification is based on the results from the uncured propellant and intermediate products use.

Ammonium Perchlorate Propellants

AP composite propellants generally fall into the Type A Thiokol hazards classification. The only problem encountered to date with the uncured propellant is detonability of very high solids composition. Formulations with up to 88.5 percent solids have been found to be nondetonable. A series of detonability tests, conducted on high solids materials, indicates that critical solids loading is between 90 and 92 percent. The study also showed that 94 percent solids compositions are highly detonable. The critical diameter was found to be less than 3/4 inch. The material detonated when subjected to shock from a No. 8 blasting cap and it will transit from burning to detonation.

Hydrazinium Diperchlorate Propellants

Hydrazinium diperchlorate (HP_2) oxidized propellants are normally more hazardous than the AP oxidized type. The Thiokol hazards classification usually places them in the Type B range. The Type B classification is assigned because of impact sensitivity, friction sensitivity, thermal stability, and detonability. Because of the greater hazards associated with HP_2 propellants, a special test series was conducted to define the extent of hazard present in a specific manufacturing environment. The tests were conducted simulating actual process conditions to determine the result of accidental ignition during mixer scrapedown.

Steel containers, approximately the size and shape of the mixers to be used, were fabricated. The mixer blade configuration was simulated with steel plates welded onto steel tubing. The simulated mixers were loaded with 70 percent more propellant than is normally mixed. The propellant was loaded in large chunks allowing air voids and folds throughout the mass. The overloading of the mixer and the presence of air voids in the HP_2 tend to increase the violence of reaction from flame ignition. The propellant was ignited with a standard Thiokol burning pit (soft) igniter. The tests were monitored with seismic measurements, photography, and visual observation. A total of three tests were conducted.

For the first test, the blades were oriented to offer minimum confinement. The igniter was located on top of the propellant against the mixer wall to simulate accidental ignition from scraping. The second test differed from the first only in that the blades were oriented to offer maximum confinement. For the third test a pair of flameproof coveralls was hung adjacent to the mixer. The coveralls were positioned to simulate a person reaching toward the opening of the mixer. The right side of the coveralls was less than 2 ft from the mixer, with the left arm extended to about four feet from the mixer. The mixer blade position was the same as in the second test. The igniter was forced about 1 in. below the surface of the propellant, in the center of the mixer to simulate accidental ignition from impact against one of the blades.

In all three simulated mixer tests loud reports followed ignition, however, seismic shock was not recorded. Most of the propellant burned extremely rapidly with flames shooting 50 ft from the mixer. However, pieces of ejected propellant burned relatively slow. In the first test, the reaction did not damage the container. However, on the second and third tests there was evidence of a pressure rise under one end of the blades. In one test, the blade locking pin was torn loose and bent up on one end. In the third test, the locking pin was in place, but bowed up about 1 inch.

The coveralls adjacent to the mixer were still intact. Two darkened areas were visible on the right side, but the heat was not sufficient to damage the material.

Of the three tests conducted, the first was the least violent. The blades, on this test only, were located to offer least confinement. This confirms, as expected, that confinement has a significant effect on burning material. Processing hazards can be reduced by proper positioning of the blades prior to entering the mixer building.

Test results indicate that a person wearing flameproof overalls and standing near the mixer might not have been harmed badly during the test. However, the test was conducted in the open, and the mixer opening was not directed toward the coveralls. Hence, this test is not completely applicable to process situations. Overhead obstructions such as a building roof would deflect the flame back to the area adjacent to the mixer. Also, a person might conceivably be standing directly in front of the mixer opening. Therefore, an aluminized cloth flame suit that offers better protection than regular flameproof coveralls is used. In addition, operator exposure to the mixer opening is kept to a minimum.

CONCLUSIONS

Thiokol's Wasatch Division has developed a hazards evaluation procedure for all phases of solid propellant development and manufacture. This procedure is considered a major step toward elimination of process incidents. The procedure was designed for hazard evaluation of composite propellants and constituents being manufactured using procedures and facilities at Thiokol's Wasatch Division. However, because other companies are using similar procedures and facilities most of the information can be utilized by solid propellant and explosive development and manufacturing organizations to improve their operations safety.

The program conducted to completely characterize the explosive properties of ammonium perchlorate provided information used to improve safety in storage, handling and processing of this material. Ammonium perchlorate of small particle size was found to be significantly more detonable than nominal 200 micron as received material. However, none of the ammonium perchlorate tested from 7.7 to 62.4 micron would transit from burning to detonation in heavy confinement. Therefore ammonium perchlorate can still be stored using existing quantity-distance criteria when no other explosive material is present.

The hazard test program conducted on hydrazinium diperchlorate, a high energy oxidizer being used in experimental composite propellants, showed that several procedure and facility changes are needed to provide safety comparable with that for operations using AP oxidizer. Hydrazinium diperchlorate is more hazardous than ammonium perchlorate, being more detonable and more sensitive to impact, friction, electrostatic, and direct heat environments. Unlike ammonium perchlorate, hydrazinium diperchlorate will readily transit from burning to detonation.

Drying was the most hazardous operation in manufacture of hydrazinium diperchlorate because of the material's low thermal stability. This hazard was reduced to a safe level by drying HP_2 under vacuum at approximately 170° F, continuous removal of acid vapor and by the incorporation of a water deluge system in the dryer. To insure that each batch HP_2 is stable a series of thermal stability tests is conducted.

Some hazardous intermediate propellant compositions have been evaluated. Tests proved that ammonium perchlorate rich propellant, a material present during early mixing, is detonable and will readily transit from burning to detonation. However, this material poses no particular hazard to personnel, because the hazard exists only during remote controlled operations.

One significant safety hazard resulted when two propellant ingredients became separated from the mix and mixed with each other on the mixer freeboard. Both materials, ammonium perchlorate and ferrocene, had been tested previously and were considered relatively insensitive; however, the mixture of these two ingredients proved electrostatic and friction sensitive. Elimination of this hazard to operations personnel required an operational change for safe removal of the sensitive composition.

Tests of final propellant compositions manufactured at the Wasatch Division have shown the AP oxidized propellants can be processed safely and are classified as fire hazards only.

Some detonability, sensitivity, and stability problems have been encountered with experimental propellants such as those using hydrazinium diperchlorate. These hazardous conditions have been eliminated by such changes in equipment and/or procedures as the elimination of motor cutback operations by form casting.

LEISK, AEROJET-GENERAL CORP.: Going back to your discussion of AP special tests, you indicated fire exposure, bullet impact, and air dispersed dust. Discussing fire exposure, I believe I understood you to say that the AP burned but did not detonate.

PLATT: That's correct.

LEISK: Was it uncontaminated material?

PLATT: This was pure AP but we assume that under shipping conditions in an aluminum container, the material would be contaminated with aluminum after it got hot enough to start melting the aluminum container. We observed no reaction although this container was melted somewhat.

LEISK: How did you obtain ignition of the uncontaminated perchlorate?

PLATT: We built an extremely large fire around the container and let it sit until it heated up and ignited?

LEISK: The uncontaminated AP actually ignited and burned under those conditions?

PLATT: It was partially burned, it didn't all burn. It was completely confined, the container was closed on all sides so the heat would build up pressure and the AP was partially burned, it wasn't completely burned.

VOGT, NPP: Your micron size, I think was 8.7 and 400, if I recall. Is this an average micron on a micromirograph or a very selective cut, I'm speaking of the very small micron size?

PLATT: This was a micromirograph measurement of a sample that we received from American Potash and they called it 15 micron. On the board I showed all micromirograph measurements used at our plant.

VOGT: You used the classification system of your own, A, B, and red line, with A I feel being relatively insensitive. I believe if I interpreted the data right on your slide, there was very little difference between your 400 micron material and your 7.7 or 8 and your own tests or did I pick up something wrong there? I saw little difference there.

PLATT: There is very little difference.

VOGT: Yet you ran the ICC test and you came up with a Class A on two materials?

PLATT: Yes, that's right, but the ICC test or military tests have an impact test, the rest are detonability type tests and the material that they detonate.

VOGT: Then your final conclusion in your own plan at present on fine micron material, you still consider a Class B in processing quantity-distance-wise in setting up your criteria?

PLATT: Yes we do, because we ran, as you saw, an extremely large number of tests to try to see if we could get the material to transit from deflagration to detonation. It would not in any case.

KING: In your deluge tests on the HP2 samples, I think you used a 1-pound sample, is that correct? And you mentioned they burned for 10 seconds?

PLATT: Yes.

KING: It seems like a long burning time for that sample, how did you initiate that fire?

PLATT: We initiated it with our standard burning pit igniter which is simply a chunk of propellant with a micron wire.

KING: What geometric shape did the sample take?

PLATT: These 1-pound samples were placed in a cardboard carton, sort of an ice cream type of carton and the igniter was placed on top in the center of the sample.

LANDAU, NOTS: What was the particle size of the HP2?

PLATT: The tests varied on the HP2. We found very little difference in the particle size which is the reason I didn't mention it. We had particle sizes ranging from about 50 to 5 to 600 in this series of tests.

LANDAU: In the comparison you were comparing 50 micron and above with 8 micron for AP?

PLATT: Yes.

Panel on Supporting Studies for the Design of Facilities to Reduce the Risk of Explosion Propagation

Panel Leader - S. Wachtell - Picatinny Arsenal, Dover, N. J.

Panel Participants -

Richard Rindner - Picatinny Arsenal

Norval Dobbs - Ammann & Whitney, Consulting Engineers

William Roberts - OCE, Ohio River Division Labs.

Billy Sullivan - OCE, Waterways Experiment Stn.

S. Wachtell - Picatinny Arsenal

Introduction

At previous meetings, Picatinny Arsenal presented an approach undertaken to study the problem of design of structures for the prevention of explosion propagation in manufacturing and storage facilities. This program has been supported by the Armed Services Explosives Safety Board (ASESB) and was initiated after a good deal of study had shown that the existing criterion for propagation prevention (the 1-foot reinforced concrete "substantial" dividing wall for 5000 lbs. of high explosives) was inadequate. This criterion had originally been specified only to prevent simultaneity of propagation and was not intended to be applied to situations where total prevention of propagation was required. A series of tests run by the ASESB from 1960 - 1962 showed that the 1-foot substantial dividing wall was good for less than 275 lbs. of explosive where assurance of non-propagation in the adjoining bay was essential.

The Picatinny Supporting Studies program was designed to investigate many aspects of propagation and wall design. This included (1) The Donor Output, (2) The response of the protective Structure, and (3) The response of the Acceptor.

Figure 1 shows schematically, the analysis of a typical explosive system. Below is a brief outline of the effects considered in the program:

1. The Donor Output - The output of the donor weapon or explosive is affected by many factors such as type of explosive, physical shape, casing thickness, the geometry of the storage configuration, etc.

2. The response of the protective structure - This is affected by the Donor output, the strength and construction of the wall and the geometry of the storage configuration.

3. The acceptor response - The acceptor in a particular case may be another weapon or explosive, various types of equipment, or personnel. This leaves a very wide range of sensitivity to be considered. However, up to this point in our program our studies have been oriented to prevention of propagation in acceptor weapons.

Obviously, in any explosive system, the requirements for barricade protection depends on both donor output and acceptor sensitivity.

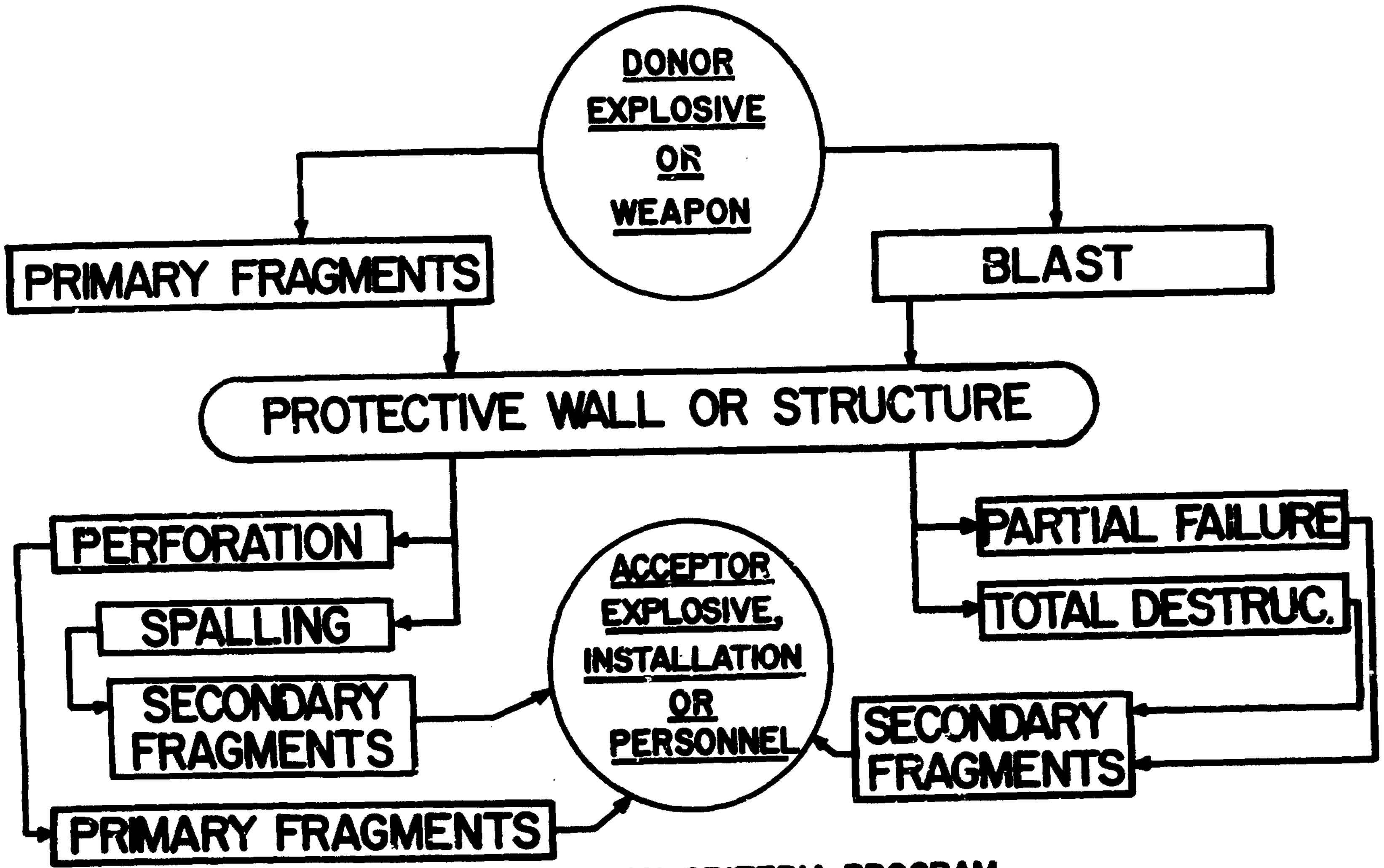
To develop the information for the overall design criteria, a number of subsidiary investigations were undertaken. We have assembled here a distinguished group of people who have worked on these investigations and who will briefly discuss the work they have done.

1. To establish the mechanism of propagation, experiments, to determine the sensitivity of acceptors to primary fragments from the donor weapon and to secondary fragments from barricade break-up, were performed by the Naval Ordnance Test Station, China Lake, Cal. and by the Arthur D. Little Co. under contract to Picatinny Arsenal. This is reported on by Mr. R. M. Rindner of Picatinny Arsenal.

2. In the design of high capacity structures, (a) the principles established from scaled and full scale test results and the rationale used to accomplish wall design will be discussed by Mr. Norval Dobbs of Ammann & Whitney. (b) The use of fibrous reinforcement to increase concrete strength and reduce secondary fragment velocity will be discussed by Mr. Wm. Roberts of the Office, Chief of Engineers, Ohio River Division Laboratories. (c) A program to investigate methods of attenuating shock transmitted through a wall has been undertaken by OCE Waterways Experiment Station and will be reported on by Mr. Billy Sullivan of that station.

3. Methods used in testing reinforced concrete designs at NOTS and at Picatinny will be discussed by myself.

4. Studies to validate the concept of scaled testing which was used to generate the majority of design data available to date, will be discussed also by myself.



SAFETY DESIGN CRITERIA PROGRAM

TYPICAL EXPLOSIVE SYSTEM ANALYSIS

FIGURE 1

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ACCEPTOR SENSITIVITY TO FRAGMENT IMPACT

by

Richard Rindner, Picatinny Arsenal

Explosive materials can propagate by impact of primary fragments resulting from shattering of explosive casing or by secondary fragments resulting from break-up of the protective structure.

Part I - Primary Fragments

Analytical studies on primary fragments (Reference 1 and 2) have resulted in development of methods for (1) predicting the vulnerability of an explosive system to high order detonation in terms of geometry of the system and explosive properties and (2) calculation of safe distances for any degree of risk. The relationships involved in this phase of our program were presented at the 1st and 2nd Safety Seminars and are also detailed in Reference 3.

A confirmatory test program was conducted at the A. D. Little Test Facility in Hinsdale, New Hampshire, in which steel fragments of known mass and velocity were projected into uncased explosive of Pentolite and Cyclotol (Reference 4).

The experimental work utilized an explosive technique for projecting rectangular fragments of 0.2 - 3.0 oz. against explosive charges at velocities both above and below that required for detonation. The explosive launching technique, as shown on Figure 1, consisted of placing a fragment, its metalic surround and an attenuating or buffer sheet of lucite on the forward flat face of a cylindrical explosive donor. The lucite spacer or buffer plate provided the means for controlling the launch velocity. The fragment was surrounded by four pieces of steel of equal thickness that prevented deformation at the edges of the fragment during the early stages of launch. Those steel pieces were thrown to the side on firing the fragment.

Aiming procedure is shown on Figure 2. The donor charge assembly was placed at the top of the 7 foot high stand and the acceptor charge was centered vertically below. The fragment velocity was measured by two independent methods. The first, shown on Figure 2,was a timing device consisting of 3 aluminum screens and an interval timer. The screens were located at a specified distance between the donor and acceptor charges. Velocities were computed from the measured fragment travel time and the known distance between the screens. The second and more reliable method of measuring fragment velocities utilized a high speed, Dynafax camera located approximately 20 feet from the flight path and viewing approximately the last four feet of fragment travel including target impact. Figure 3 shows a typical film series of a fragment in flight.

The results of firings against the bare Pentolite and Cyclotol charges including the predicted boundary (minimum detonation) velocity curves are presented on Figure 4 and 5 respectively. In general, the data conform to relationships developed analytically for small and intermediate fragments while the detonation velocity for heavy fragments fired into the bare Cyclotol charges was higher than predicted by approximately 40%. This would indicate that the mass-velocity relationship may require adjustment for a more accurate prediction of sensitivity to impact by heavy fragments. However, the current predicted values for the boundary velocity tend to be conservative and hence are satisfactory for design purposes where safety is the prime consideration.

More tests will be conducted to better define the trends with increase in fragment size as well as to investigate the effects of other variables on boundary detonation velocity.

Part II - Secondary Fragments

The Large Scale Cubicle Tests conducted under the auspices of the Armed Services Explosives Safety Board (Reference 5) indicated that the secondary fragments (fragments resulting from breakup of protective barrier caused by high order detonation of the donor explosive) are the most likely cause of propagation of detonation into the acceptor charge. Since there was neither analytical nor previous test data available, an extensive experimental program was initiated to determine the threshold velocity of fragment (or fragments) that would cause detonation in the explosive charge. Two experimental methods (both developed by the Naval Ordnance Test Station personnel) were selected from several investigated (Reference 6).

The first method as shown on Figure 6 consisted of a rocket-powered sled (track method) designed to throw a mass of concrete and aggregate fragments at an explosive charge at velocities within the range of those occurring in full scale cubicle tests. The main feature of a rocket-powered sled was a test vehicle and fragment container which was attached to the top of the motor as shown on Figure 6. Water breaking action was supplied by partially filled polyethylene water bags fastened to the last 10-15 feet of track (Figure 7). Sled deceleration was accomplished when the wedge on the front of the sled hit the water-filled bags fastened to the track. Fragment specimens used weighed a total of about 70 lbs. and contained approximately 50 lbs. of broken-up concrete and 20 lbs. of aggregate.

The test vehicle was accelerated to a known velocity followed by the release of the fragment through the frangible cover of the container by water-brake deceleration of the vehicle. The velocity of the vehicle was controlled by the number of rocket motors used, by changing the distance of the ignition point from the point of water-brake activation and by varying

the weight of the sled.

A second method, the ground mortar facility, was developed to provide a less expensive test method to produce a large quantity of fragment impact data.

The ground mortar facility is a muzzle-loading shotgun, 10 inches in diameter, manufactured from standard thick-walled seamless steel tubing. As shown in Figures 8 and 9 the tube was buried in the ground, throwing fragments vertically at the acceptor charge suspended above the mortar muzzle. The fragments were thrown at selected velocities by varying the amount of propellant in the steel cup at the breech end of the mortar tube.

To measure fragment velocities (in both the track and ground mortar method) high speed cameras as well as carbon rods were used. Using the camera technique, velocity measurements were made by counts of time of frames and reference distances of mass travel.

The carbon rod technique (Figure 9) used two sets of carbon rods placed five feet apart above the muzzle of the ground mortar. The projected fragment broke both sets of carbon rods giving a measurement of its velocity.

The two systems (camera and carbon rod technique) provided a check and back-up for each other. More than 100 tests were performed by both methods using primarily 70 lbs. concrete rubble as an impacting fragment. The ground mortar utilized, in addition to the above 70 lbs. of concrete aggregate, 70 lbs. of dry plaster sand and 35 lbs. of rubble. The fragment velocities chosen for investigation corresponded to those that were recorded during the destruction of walls in large scale cubicle tests. The lowest recorded velocity at which detonation occurred (the threshold detonation velocity) was approximately 400 ft/sec. for Comp. B. Both methods (track and ground

mortar) gave comparable results. This velocity compares very favorably with the threshold detonation velocities recorded in the Full Scale Cubicle Tests. Subsequent tests with PBX explosives showed detonation velocities substantially lower than those mentioned previously.

The tests conducted to date point to secondary fragments as the main cause of detonation propagation. Because of insufficient number of rounds fired, the effects of varying the test parameters (such as fragment size and shape, acceptor size and degree of anchorage etc.) has not yet been investigated.

An extensive experimental program for quantitative determination of those parameters on threshold detonation velocity is planned for the near future.

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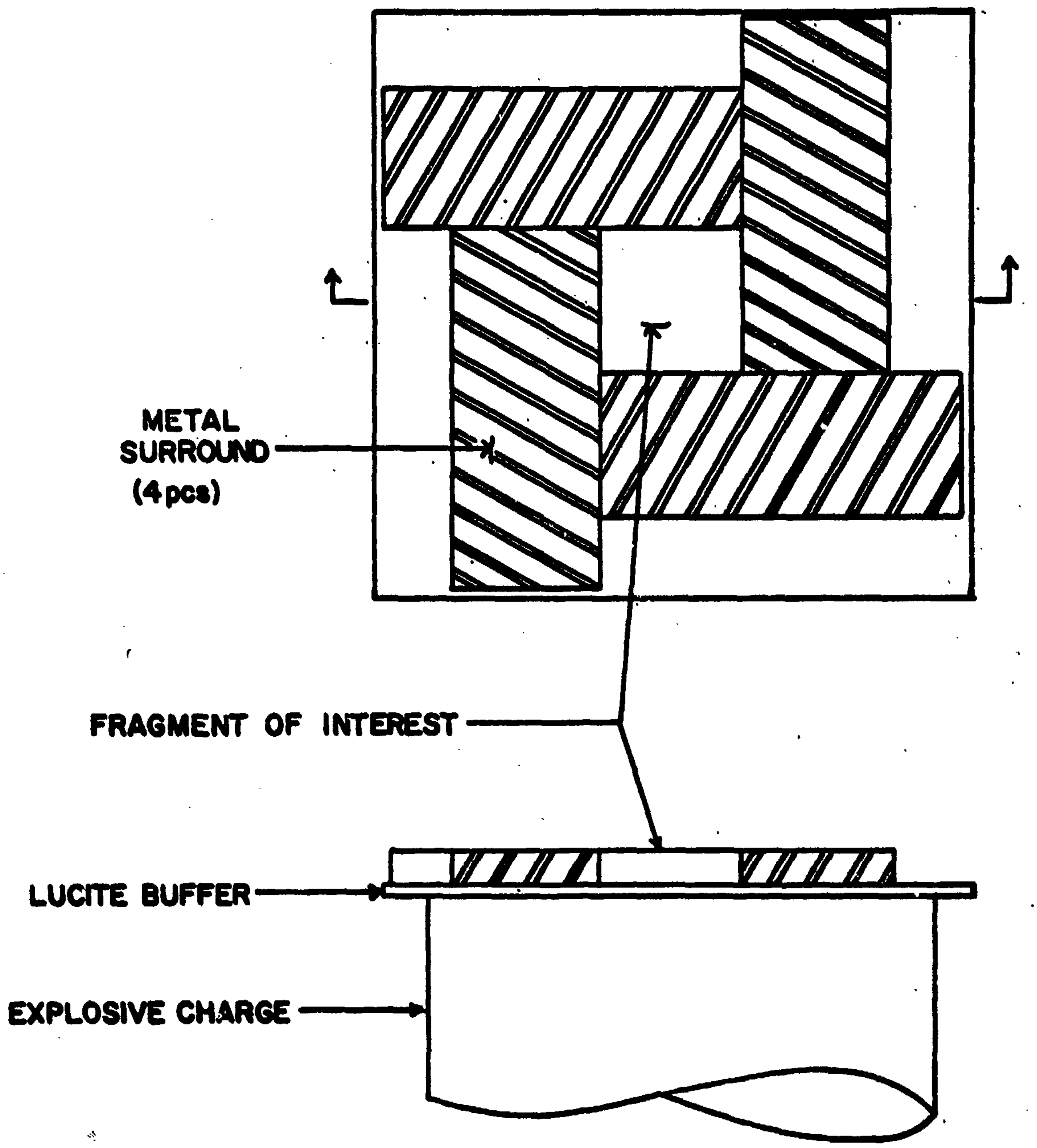
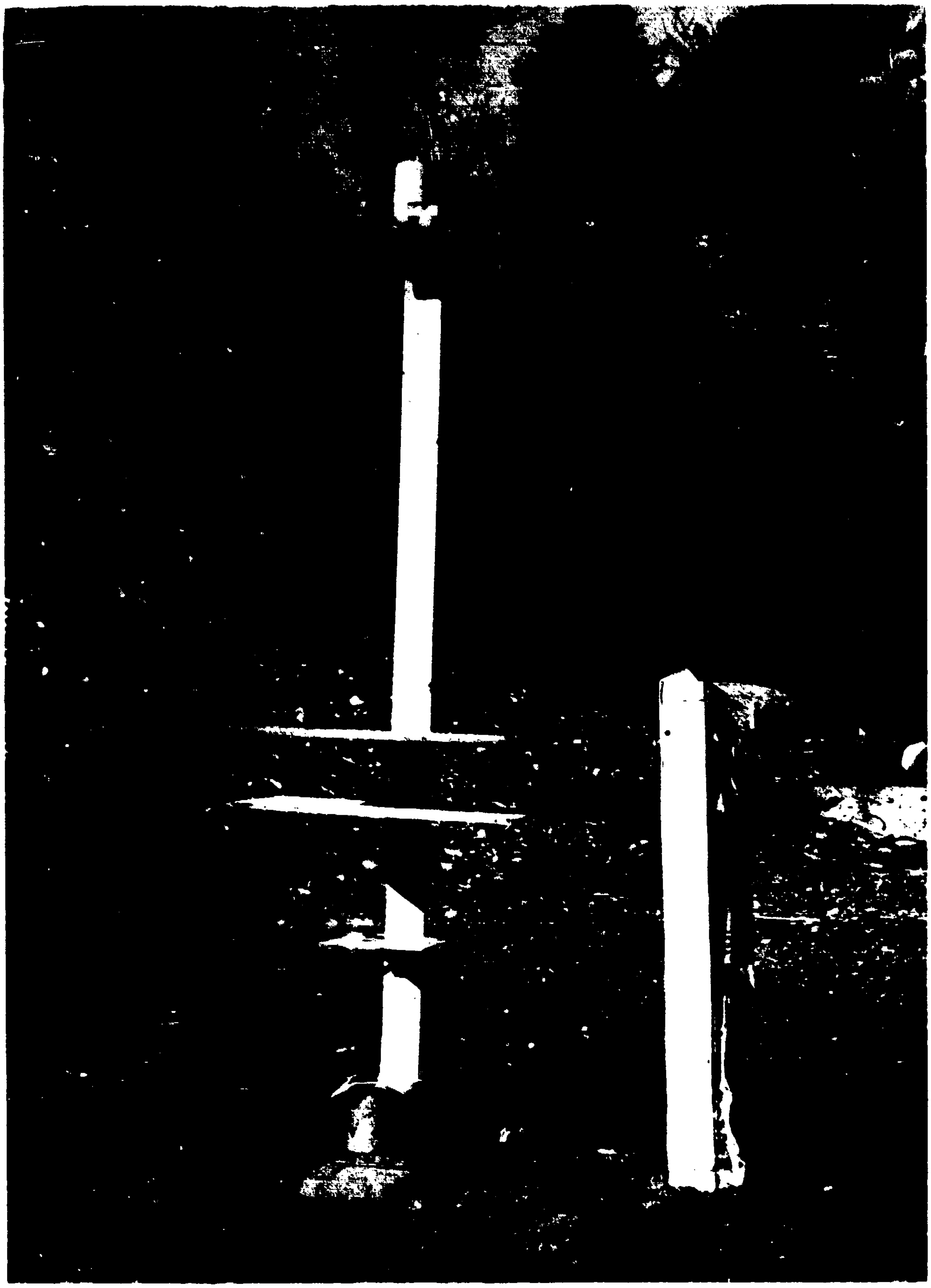
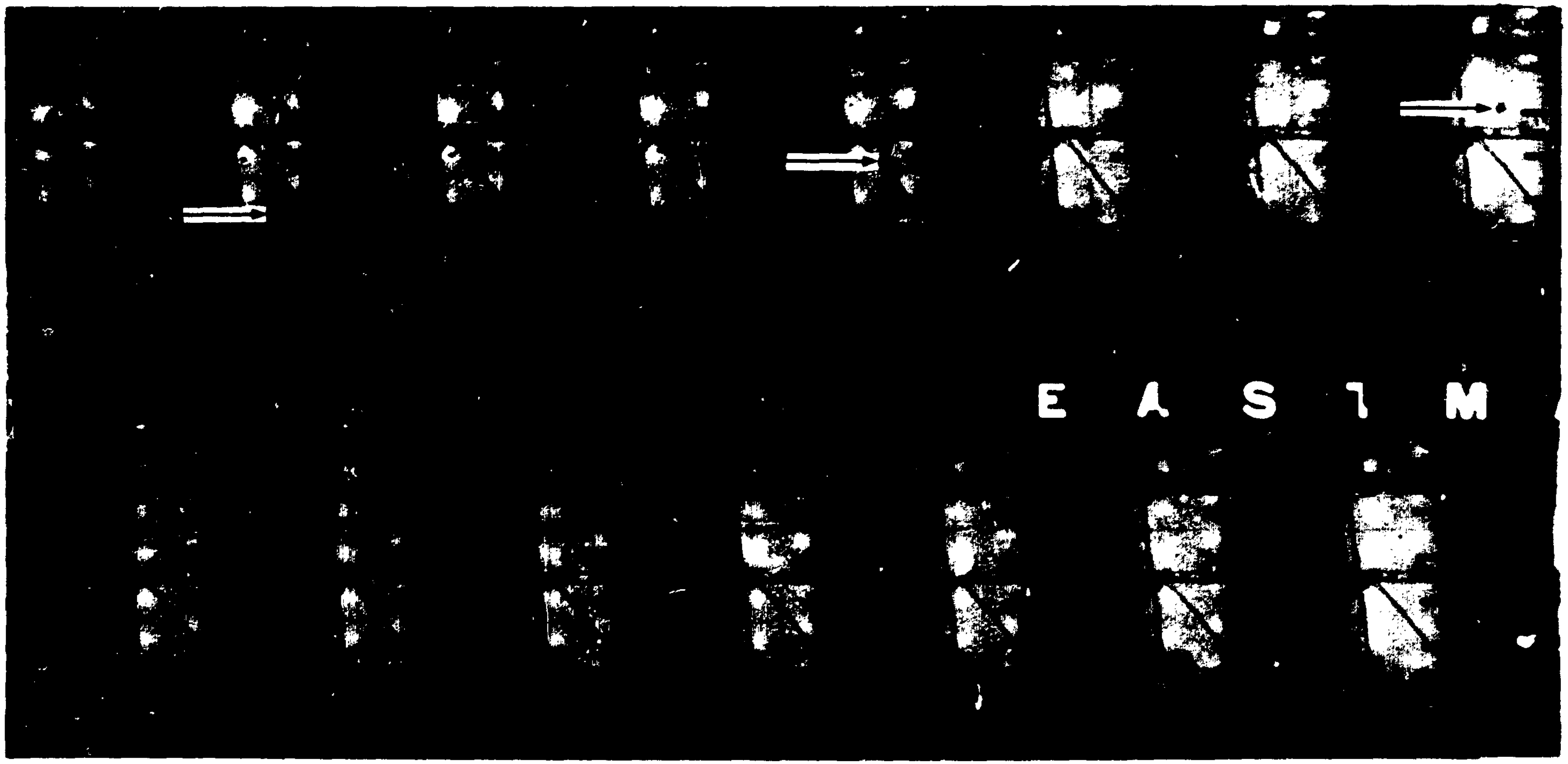


Figure 1. Fragment Arrangement with Metal Surround



Test Arrangement Ready for Firing
FIGURE 2.



High Speed Photograph Fragment in Flight

Run #54--2080 ft/sec--2.85 oz fragment

FIGURE 3.

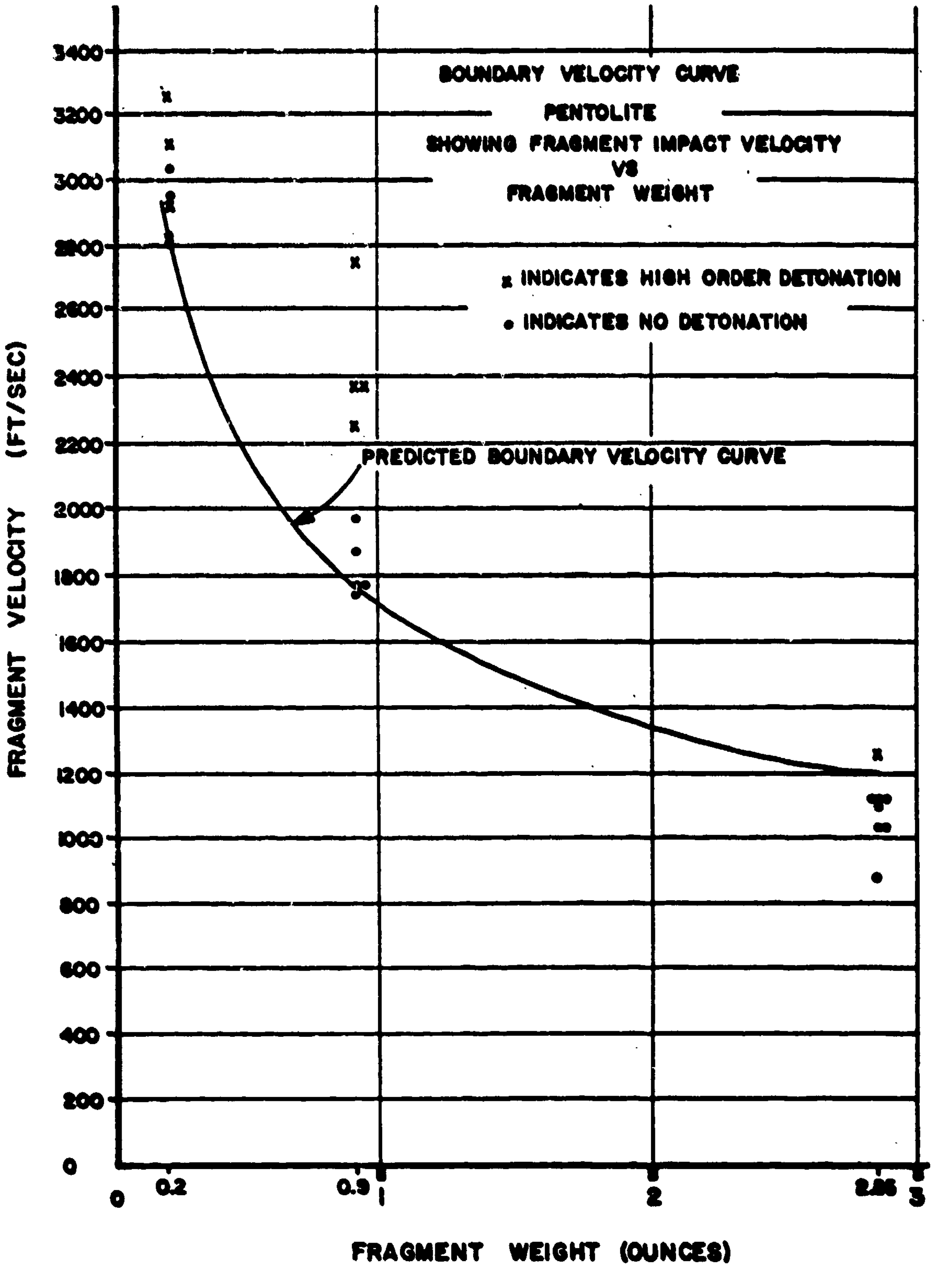


Figure 4. Pentolite - Fragment Impact Velocity vs Fragment Weight

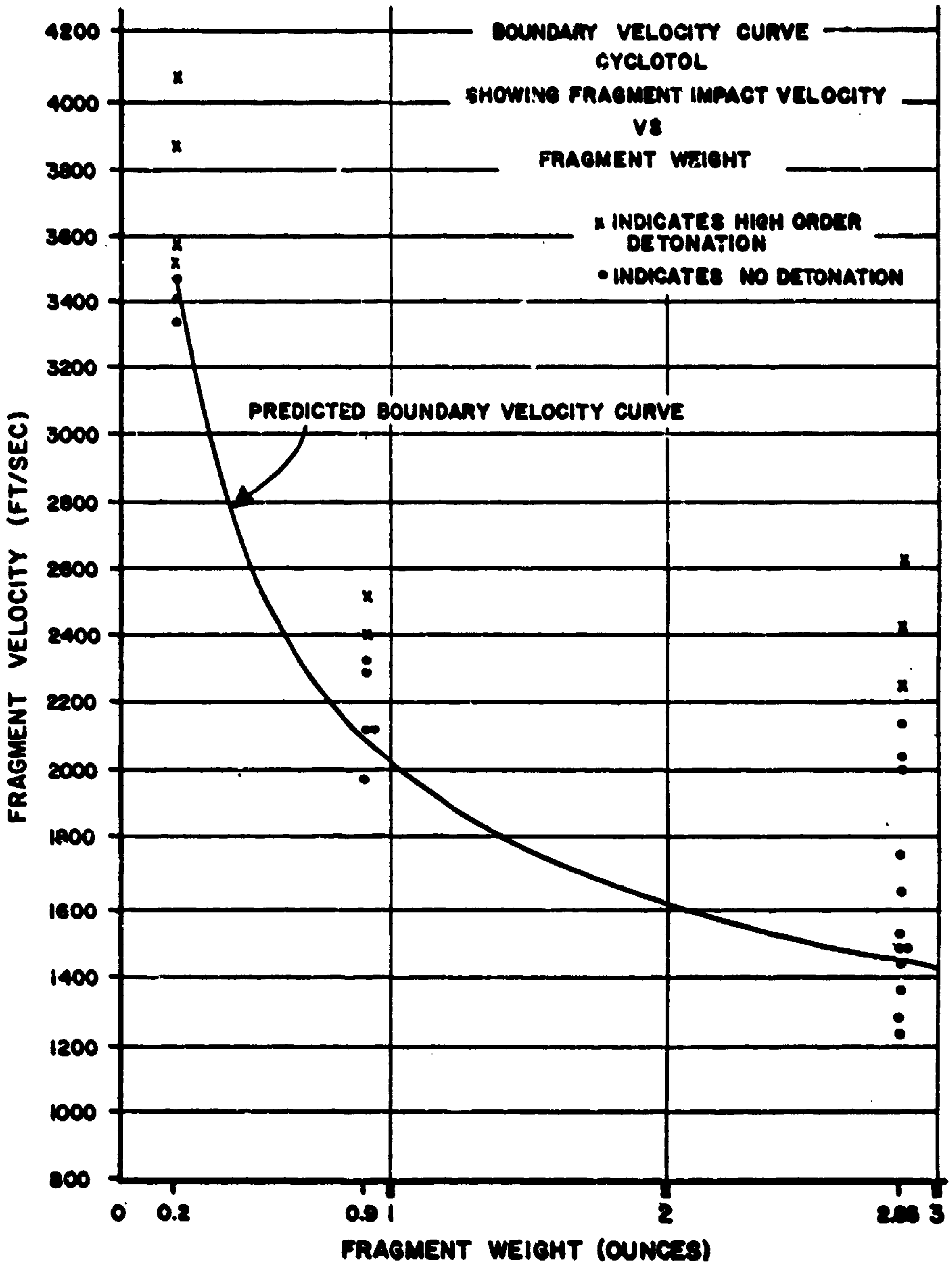


Figure 5. Cyclotol - Fragment Impact Velocity vs Fragment Weight

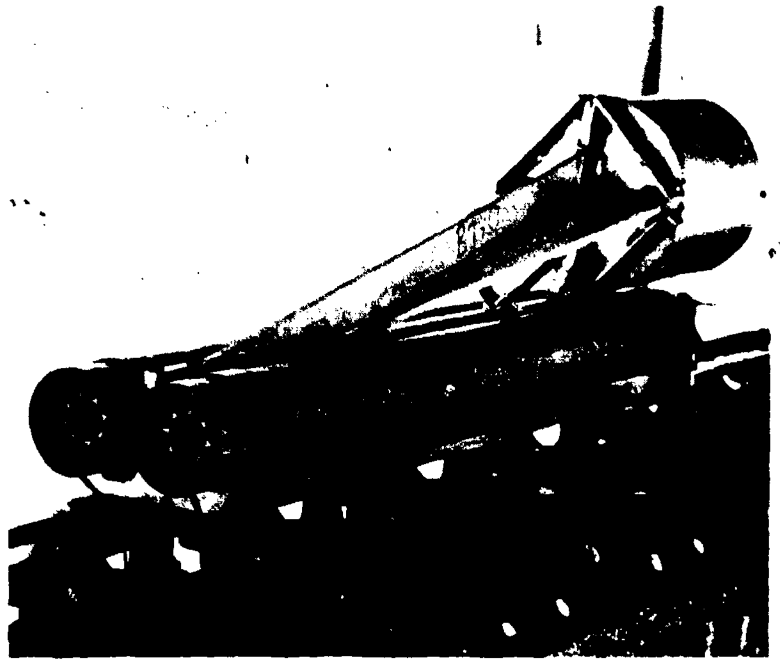


Figure 6.. Fragment Sled - Rear View
(Showing Auxiliary Structural Members for Test Item Support)

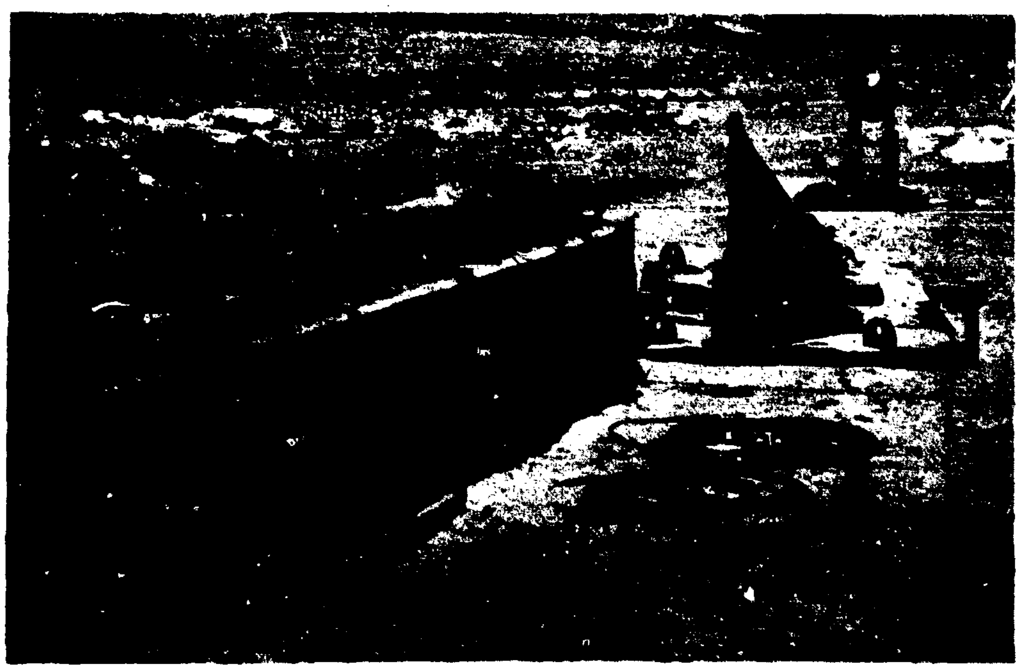


Figure 7.. Test Setup Details
(Water Brake, Deflector Plate, and Acceptor-Charge Target)

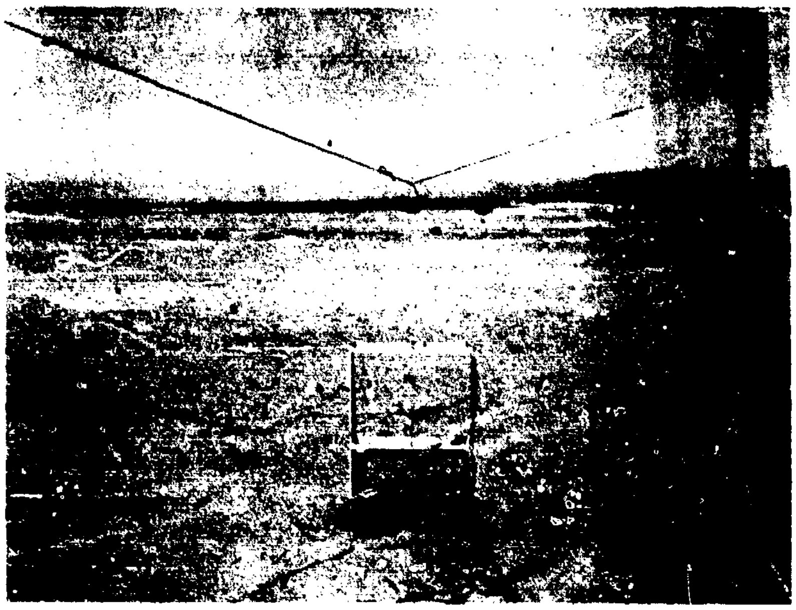


Figure 8. Ground Mortar Test Setup

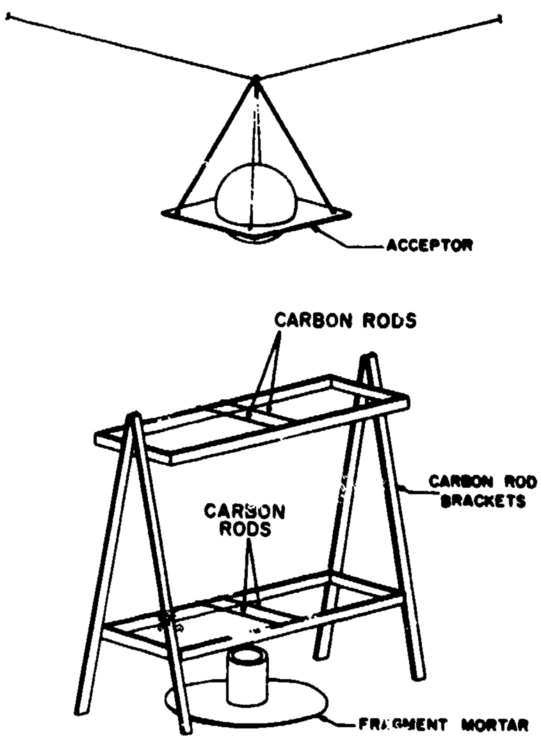


Figure 9. Ground Mortar Test Setup With Carbon Rods in Position

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THE DESIGN OF MORE-EFFECTIVE CUBICLE-TYPE
PROTECTIVE BARRIERS FOR EXPLOSIVE STORAGE & MANUFACTURING FACILITIES
by

B. Cohen and N. Dobbs, Ammann & Whitney

INTRODUCTION

The need for new and improved methods of design of structures for the safe storage or manufacture of explosives has existed since the turn of the century. Over the years, as such structures were built, guide lines evolved for the design of protective walls. Refinements to these guide lines were made based on available data in conjunction with theoretical considerations. These refinements, which were concerned primarily with explosive quantity-distance relationships for large quantities of explosives located at relatively large distances from protective barriers, expressed the protection afforded by the barrier in terms of probable structural damage. The procedures used did not include a detailed quantitative basis for assessing the degree of protection afforded by blast walls or other protective elements. This approach has been found to be generally inadequate for present-day design requirements. Structures built under these guide lines and quantity-distance relationships as protective shelters, barricades, and substantial dividing walls remain in use today.

Current methods of manufacturing and storage of explosives and explosive materials (chemicals, fuels, and propellents, etc.) allow less space for a given quantity of material than previously per-

mitted. The congestion and concentration of explosive materials have increased the possibility of the propagation where one accidental explosion initiates detonation of other explosive material in the facility. Moreover, in smaller areas more extensive damage can result, especially in the vicinity of the explosion, due to the amplification of the blast effects in the area of high-explosive density. It is evident that the requirement for more accurate design techniques has become essential. The purpose of this paper is to describe the basis for a rational method of design and to present corroboratory test data.

This method of design accounts for the close-in effects of a detonation and the associated high pressures and non-uniformity of the blast loading on a protective barrier. The dynamic response of the structure is calculated and the structure detailed to provide the properties necessary to supply the necessary strength and ductility. Development of this procedure was directed primarily towards blast load analysis and protective barrier design for explosive systems contained in cubicle type structures. This approach is general and has application to design for other explosive environments as well.

For design purposes, one must relate the three components of an explosive system in order to assess the safety of the overall system. These include: (1) the donor system (explosive material) which produces the damaging output, (2) the protective barricade, walls,

structures and/or distances which reduce the donor output to a tolerable level and, (3) the acceptor system (explosives or personnel). The blast environment produced by the donor system within the protective structure and the dynamic response of the structure to the explosive output are described in the following sections. Explosive structures tests, which demonstrate the use of the new design techniques for protective structures are also presented. The acceptor system is discussed only as it relates to the other two components of the explosive system.

The design techniques, reported here, have been developed by Ammann & Whitney under contract, DA-28-017-AMC-423(A), to Picatinny Arsenal as part of their Supporting Safety Studies Program for the Armed Services Explosive Safety Board.

PERTINENT EFFECTS OF HIGH EXPLOSIVE DETONATIONS

Explosive Output

The explosive output of the donor system is in the form of (1) air blast overpressures (hereafter referred to as pressures) as a function of time, and (2) projected fragments from cased explosives. For the design of the protective barrier, the blast pressures and the impulse loads (area under the pressure-time curve) resulting from the detonation are of prime importance. With respect to the overall safety of a facility, however, the damaging effects (personnel injury or sympathetic detonations) of casing fragments can be equally important.

The magnitude and distribution of the blast loads on a barrier are a function of the following factors: (1) explosive characteristics, namely, type of explosive material, energy output (high or low order detonation), and the weight of the explosive; (2) the location of the explosive relative to the barrier and/or the acceptor; (3) the magnification and reinforcement of the pressure wave by its interaction with the barrier and/or other obstructions; and (4) the duration of the positive pressure phase.

Although quantitative data is given in this paper for the reflected blast output of TNT based-explosives, the method can be extended to include other potentially mass-detonating materials such as high energy propellents.

Interior Blast Loads

When an explosion occurs within a cubicle (Fig. 1), the peak overpressures associated with the blast output will be extremely high. However, because of the short duration associated with close-in high explosive detonations, one can design structures for the dynamic impulse loading rather than for the peak overpressures, as required for the relatively long-duration associated with a nuclear explosion.

In confined quarters amplification of the initial blast output (free-air pressures) due to its reflection within the structure will occur. At any given point on a particular reflecting surface, the total impulse loading is a combination of contributions from the initial shock and from shocks reflected from adjacent surfaces.

An approximate method for the calculation of the total impulse for design purposes was developed in connection with the Supporting Studies Program (Ref. 1). The total reflected impulses acting on various points on each surface of the cubicle have been calculated and then integrated to give the total impulse loads acting on the surface. In order to simplify the calculation of the response of a protective barrier to these applied loads, the total impulse is assumed to be distributed uniformly giving an average value of the individual impulses acting on any one surface.

Figures 2, 3, and 4 present some typical average scaled unit impulse versus scaled distance curves for simple cantilever barriers, side walls, and back walls. As shown on these charts, the parameters which are necessary to describe the blast environment are structure configuration and size, charge location, and charge weight. Because of the wide range of these parameters, the procedure for determining impulse loads is presently being programmed for solution on a digital computer.

BASIS FOR STRUCTURAL DESIGN

Modes of Structural Response

The response and the required restraining capabilities of a protective cubicle and its elements to an explosive output depends on (1) the properties of the donor system, described previously, (2) the sensitivity of the acceptor system, and (3) the physical characteristics (materials, strength and configuration) of the structure itself. The donor system will establish the loading on the structure's surfaces, whereas the acceptor system and the physical characteristics of the structure will govern the restraining capabilities required to resist the applied loads. The restraining capabilities can be expressed in terms of two modes of response of the structure: (1) the ability to deflect under the applied loads (ductile mode) and (2) the brittle mode which is associated with partial or total failure of the structure.

Examination of the results of previous tests (Refs. 2, 3, and 4) of full- and scale-model cubicles and reinforced concrete slabs indicated that the individual elements with ductile reinforcement were able to undergo deflections of less than one-fiftieth their spans with well defined cracking (Fig. 5) before collapse occurs in the form of fragments (Figs. 6 and 7). The magnitude of the deflection prior to failure (Fig. 8) and the type of failure were found to be a function of the type, amount and details of the reinforcing steel. It was observed, that with the reinforcement of a Substantial Dividing Wall (Ref. 5,

hereafter referred to as Standard Wall), the steel (Fig. 9) and therefore, the ductility (ability to deform) of the individual members were not fully developed to their ultimate explosive restraining capacity. As a result of the limited deflection, less energy absorption (area under the resistance-deflection curve, Fig. 8) occurred prior to failure. Moreover, a major portion of the fragments were small, indicating spalling of the concrete cover over the reinforcement and a break-up of the concrete (Fig. 10) between the tension and compression layers of the reinforcement. This fragmentation of the concrete contributed to the reduction in the ductility and eventually resulted in total collapse. It may be noted that in these tests elements with welded wire fabric reinforcement exhibited smaller deflections prior to failure than those elements which utilized hot rolled reinforcing bars or annealed wire. This reduced deflection was attributed to the decreased ductility of the cold drawn wire fabric compared to the ductility of the other types of reinforcement. Also, a strength reduction, of the reinforcement at the heat affected zones of the steel adjacent to the welds of the fabric, contributed to a decrease in the energy absorbed before failure.

To develop a ductile response mode, relatively large bending strains (both tension and compression) must be developed. To assure this behavior, sufficient amounts of reinforcement, properly detailed, must be provided, otherwise the elements will fail well below their

ultimate blast load carrying capacity. Also, unless adequate strength is afforded against the high shear stresses in the region of the supports, the element will fail either in pure shear or diagonal tension. In addition, high local shears exist at the interior portions of the elements due to the non-uniformity of the applied impulse loads. If adequate reinforcement is not provided these shears may produce local failure of the elements, which, in turn, will spread and endanger the integrity of the entire structure. This local shear condition is referred to as a punching failure. It will be shown that with properly detailed reinforcement punching can be obviated.

Spalling of the concrete surfaces and formation of concrete fragments may result from blast overload (applied blast loads exceeding the capacity of the element). Spalling consists of a concrete tension failure (normal to the element's surface) and disengagement of the concrete cover over the flexural reinforcement. Two types of spalling may occur, namely: (1) direct spalling at the free surface resulting from reflection of the high pressures of the shock wave being transmitted through the concrete and (2) scabbing produced by large strains in the flexural reinforcement.

Direct spalling is usually of concern only in those facilities where personnel protection is required because resulting fragments are usually small in mass with low velocities (50 fps or less). If the ele-

ment's velocity exceeds those of the spalled fragments, then the fragments will be accelerated by the motion of the element. The velocities produced by this acceleration may be in the order of several hundred feet per second or larger. These fragments then will be of concern for both personnel and explosive acceptor protection. Velocities, of fragments formed by scabbing, are not dependent upon the shock pressures transmitted through the element and, therefore, the magnitude of the scabbing fragment velocities will only be a function of the accelerating effects of the element. Because the scabbed fragments are produced by the large strains in the reinforcement, the time to form these fragments after the initial onset of the blast pressures will be longer than the formation time of the direct spalling fragment. During the time interval between the formation of the two types of spall fragments, the element will be decelerating. Therefore, the velocities of the scabbed fragments will be less than the velocities of the direct spalling fragments produced by the element's acceleration. Although, in many cases, the magnitude of the scabbed fragment velocities may still be dangerous for both personnel and sensitive explosive acceptors. Fragments formed by failure of the structure may have velocities even higher than those of direct spalling and scabbed fragments. Here, the magnitude may be in the order of thousands of feet per second depending on the magnitude of the blast overload.

New Construction Techniques

After the review of existing data, a series of one-third-scale slabs (Ref. 6) and scaled-model cubicles (Refs. 7 and 8) were designed and testeu. The data obtained from these tests provided a basis for further development of the design and method of reinforcement.

To insure ductile action, full development of the flexural strength, and reduction in quantity and velocity of the concrete fragments of the members used in this test, a radical change was made from the reinforcement used in Standard Walls. The straight flexural steel reinforcement was substantially increased in quantity and laced together with bent diagonal bars. Lacing (Fig. 11) of the reinforcement accomplished the following: (1) the ductility of the flexural steel, including the strain hardening region, was fully developed (Fig. 8), (2) the integrity of the concrete between the tension and compression reinforcement was maintained despite cracking of the concrete, (3) the compression reinforcement was restrained from buckling, (4) the high shear stresses at the supports were resisted, (5) the local shear failure was prevented, and (6) the quantity and velocities of fragments were decreased.

The lacing reinforcement accomplished the first three items above by its ability to tie the compression and tension flexural reinforcement together. Disengagement and buckling of the flexural rein-

forcement is prevented by the lacing which, in turn, confines the cracked concrete between the two layers of steel. This confinement of the concrete also prevents buckling of the reinforcement in the compression region of the element in the later stages of the ductile mode.

Reference to the Resistance-Deflection curve (Fig. 8) will demonstrate the action of the lacing reinforcement in developing the flexural reinforcement. The ability of the lacing to prevent premature failure enables the element to deflect until tension failure of the steel occurs. With Standard Wall reinforcement, cracking and dislodgement of the concrete from between the reinforcement layers and buckling of the compression steel produces failure of the element long before the ultimate strength of the reinforcement is achieved. Some reduction in strength of an element may occur even when laced reinforcement is used. This strength reduction is produced by crushing and/or spalling of the concrete in the compression region of the element. When the concrete fails, the compression stresses are transferred from the concrete to the compression reinforcement with some reduction in the internal lever arm. Therefore, the magnitude of the strength reduction will be a function of the concrete cover. If the concrete cover over the steel is held to a minimum this strength reduction is also minimized.

Unless adequate shear strength, (equal to or greater than the flexural capacity) is provided, failure (Fig. 8) due to high

shear stresses, will occur at the support of an element. Lacing reinforcement provides this required strength by its own strength and by developing the dowel action of the flexural steel and the remaining strength of the concrete. Extension of lacing reinforcement into the supports (Fig. 12) affords the anchorage required to prevent diagonal tension. Also, because of the continuity of the lacing, pure shear failure is prevented. When individual stirrups (discontinuous) are used, pure shear failure can occur between the individual units. Fig. 13 illustrates a pure shear failure condition where individual loop stirrups were used in place of continuous lacing reinforcement.

Because of the continuity of the lacing reinforcement throughout the element, the high shear stresses, caused by the non-uniformity of the impulse loads, are resisted at the interior portions of the element.

The failure characteristics of an element with laced reinforcement differ from those of elements without lacing reinforcement. The sizes of failed sections of elements with laced reinforcement will be fixed by regions of maximum stress in the element, i.e., the location of plastic hinges during the plastic range (Fig. 8) of the ductile response mode (Fig. 14). After failure, the element between the hinges will usually remain intact. On the other hand, in elements without lacing, fragments are usually in the form of concrete rubble. Test results

show that the velocities of the larger failed sections (intact between the hinges) are approximately equal to the average velocity of the rubble where lacing is not used. This average velocity is in the order of 30 percent of the maximum velocity of the rubble. Some small fragment are produced by the reinforcement failure at the hinges. The volume of these small fragments are negligible in comparison to that of the larger failed sections. Also, the fragment velocities are small in comparison to the velocities of the rubble of unlaced elements.

Five specimens with lacing reinforcement and significantly larger amounts of flexural reinforcement than used in Standard Walls were tested. The first three specimens are one-third-scale reinforced concrete slabs spanning in one direction while the fourth and fifth specimens are one-tenth-scale and one-eighth-scale cubicles, respectively. Specimens one, two and five illustrate the development of the ductile response mode prior to failure whereas specimens three and four are examples of the mechanism by which laced-reinforced elements fail.

Specimen one (Fig. 15) developed a large deflection (11 inches = 46% of span) at the center, on a two foot span. Both the reinforcement and the interior concrete remained intact although, scabbing did occur at both surfaces of the slab. Plastic hinges were formed at both supports and at the center of the slab. Because the specimen was unrestrained at its ends, it moved inward towards its center resulting in the

large deflection-to-span ratio. In actual practice, the restraint movement, and, therefore, the deflection to span relationship would be somewhat less than that observed in this test.

In specimen two, the end section of the composite slab (two concrete panels separated by sand - Fig. 16) restrained the interior panel sections which were the loaded portions of the specimen. The restraint afforded by the end sections prevented end movement thereby producing a condition approaching incipient failure (on verge of collapse). Although the deflection to span ratio was less than in the previous test, the rotation (θ) achieved by the individual panels at their supports were in the order of 12 degrees. Specimens without shear reinforcement have been observed to fail with support rotations of less than 2 degrees. It should be noted that in this test the sand fill served as a mechanism to transfer, to the acceptor panel, a portion of the applied blast not absorbed by the donor panel. A portion of this transferred impulse load was absorbed by the compression of the sand. Also of interest is that the acceptor surface of the donor panel was scabbed while that of the acceptor panel was not. The sand tended to spread out the high peaks of the applied load thereby preventing spalling of the rear surface of the slab.

Specimen three (Fig. 17) illustrates failure at the plastic hinges developed in the element during the ductile mode of response.

It can be seen, that even though the member has failed, the sections between the hinges remained intact with only minor rubble occurring at the points of failure. Also, the compression reinforcement at the points of failure remained intact. This prevented the failed sections between the hinges from being detached from the rest of the specimen.

Specimen four (Fig. 18) also illustrates the effects of lacing reinforcement and the hinge formation on the failure pattern of an element. In this test, the back wall of a cubicle collapsed resulting in a failure which is analogous to the action of a swinging door (Fig. 18). Here, both the tension and compression reinforcement at the center and the tension reinforcement at the supports of the wall failed although the compression steel at the supports and the concrete sections between the hinges remained intact. The compression reinforcement at the supports served as pivots to produce rotational motion rather than translation of failed sections (intact between hinges). In this case, the energy, which would ordinarily be absorbed by translation, was instead transferred to the ground adjacent to the structure where the failed sections came to rest. The magnitude of the blast overload was not sufficient to completely detach the failed sections from the remainder of the structure. In other similar tests, separation of the failed sections did occur. The detached sections came to rest several feet from the point of initial impact. In these cubicle tests, fragments

produced by the reinforcement failure at the center hinge of the wall were dispersed away from the structure. The volume of these small fragments were negligible in comparison to that of the larger detached sections. Also, the fragment velocities were small in comparison to those observed in tests of Standard Walls.

The fifth illustration describes the test results of the maximum capacity test performed on the one-eighth-scale model of the bay structure used in the Scaling Tests (Ref. 8). A preshot analysis of this structure predicted a prototype capacity of 7000 pounds of uncased TNT explosive when detonated at the center of the structure (Fig. 19). Test results indicated an actual explosive capacity prior to failure approximately 10 percent higher than that predicted. In this test, the back wall, which was of composite construction, was the critical element of the structure and its overall damage approached an incipient failure condition. The tension reinforcement at the supports (back wall panels supported at the base slab and the two side walls of the cubicle and free at the top) and at the center of the donor panel failed with the compression steel at these sections still remaining intact. It may be noted, in Fig. 20, that a typical concrete yield crack pattern was formed. The acceptor panel of the back wall remained intact although the magnitude of the panel's deflection indicated that this portion of the wall was on the verge of collapse. Spalling of the acceptor surface of the acceptor

panel did occur at the supports (Fig. 21). This spalling was attributed to the high compression forces which crushed the concrete cover over the compression reinforcement. Spalling of other portions of the rear of the accepter panel was prevented despite the high-peak pressures of the blast loads.

COMPARISON OF TESTS UTILIZING STANDARD AND NEW CONSTRUCTION TECHNIQUES

The difference in results obtained using existing Standard Wall construction and the new construction techniques in blast resistant design described in this paper is illustrated by two similar explosive cubicle tests.

The structure used in the first test series was the Full-Scale C-13 Cubicle used in ASESB Phase C Cubicle Program (Refs. 9 and 10). This structure was built using modified Standard Wall cubicle construction while the second structure (Fig. 22) (One-Third-Scale Modified C-13, Ref. 12), consisted of a one-third-scale model of a revised design utilizing the type of laced reinforcement previously described.

The full-scale cubicle (Fig. 23) consisted of three reinforced concrete composite walls, with Standard Wall reinforcement, supported on a reinforced concrete base slab. The fourth side and the roof were open to the atmosphere. The dimensions of the interior floor area of the cell were 10 ft. -6 in. long by 8 ft. -5 in. wide and the clear height between the floor slab and the top of the walls was 9 ft. -0 in. Each wall had an overall thickness of five feet consisting of a three foot thick layer of sand sandwiched between two one-foot-thick concrete panels.

The floor dimensions and total wall thickness of the model

(Fig. 24) were equal to one-third those of the full-scale structure. The walls of the model were slightly higher to accommodate the wire bridge strands used to support the top of the side walls. Although, the overall scaled thickness of each wall of the model was the same as the thickness of each wall of the full-scale cubicle, the individual wall components differed. In the model, the scaled-up thickness of each reinforced concrete panel (18 inches) and thickness of sand (24 inches) compared with the respective 12 and 36 inch thicknesses of the full-scale structure. Considerably more flexural reinforcement was used in the model. The panel steel at each surface was 2.7 percent as compared with 0.16 percent for that of the full-scale structure. In addition, the flexural reinforcement of the model was tied with the use of laced reinforcement.

The scale-model was built with wall and floor slab extensions to simulate the restraint afforded by adjacent cells on the cell containing the explosion. The inclusion of such extensions would have had negligible effect on the results of the full-scale structure test.

Both structures were tested with the same equivalent scaled charge of 1640 pounds located near the floor slab and at the center of the cell.

The different results of the two tests are apparent from

Figs. 25 and 26. The full-scale cubicle was destroyed except for the floor slab which was cratered below the donor charge. The debris formed by the collapse of the walls consisted of concrete rubble and was dispersed over a wide area of the test range. The model structure approached incipient failure conditions with permanent angular rotations of the concrete panels in the order of 12 degrees. Although scabbing of the acceptor sides of the model walls did occur, the velocities were small and would not have been a source of danger for explosive acceptor systems.

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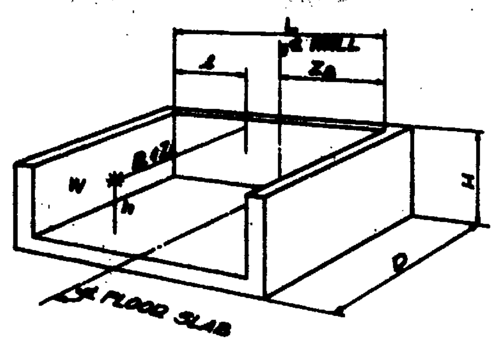

Fig. 1 CUBICLE PARAMETERS

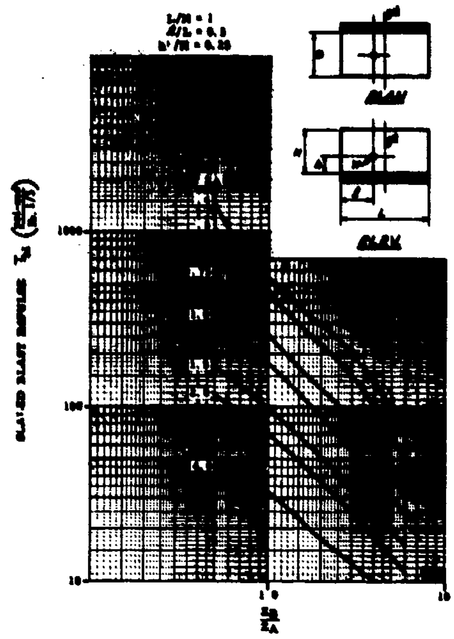

Fig. 2 TYPICAL IMPULSE LOAD CURVES (CANTILEVER WALL)

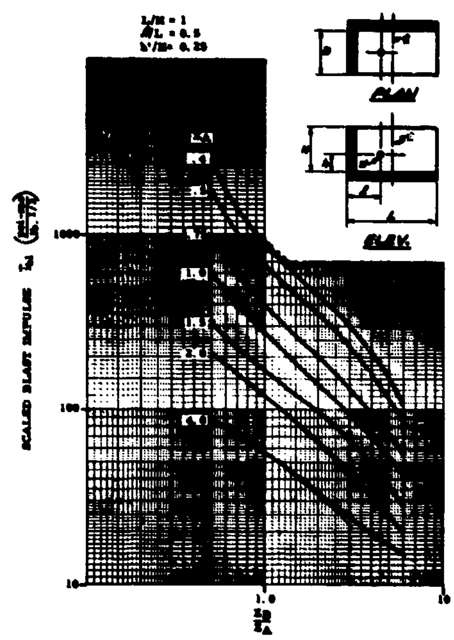

Fig. 3 TYPICAL IMPULSE LOAD CURVES (SIDE WALL)

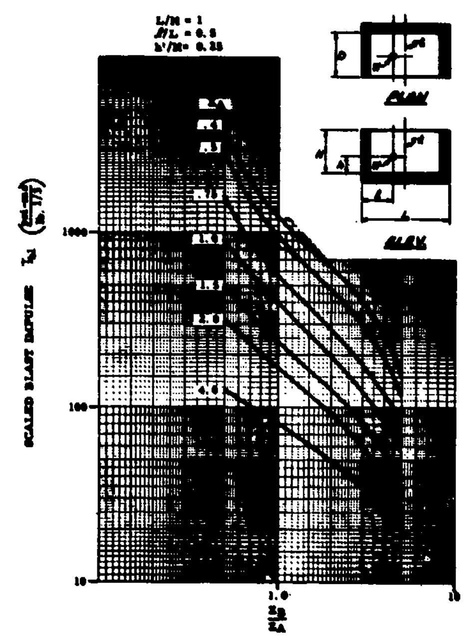

Fig. 4 TYPICAL IMPULSE LOAD CURVES (BACK WALL)

Fig 5 CRACKING OF LEEWARD (ACCEPTOR) SURFACE OF SLAB

Fig. 6 PROPAGATION OF CONCRETE FRAGMENTS

Fig. 7 PROPAGATION OF CONCRETE FRAGMENTS

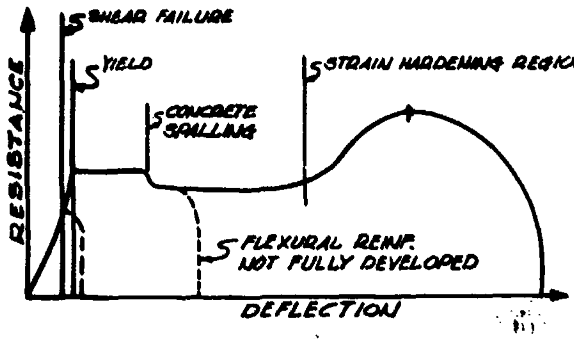

Fig. 8 RESISTANCE-DEFLECTION CURVE

Fig. 9 UNDEVELOPED REINFORCEMENT

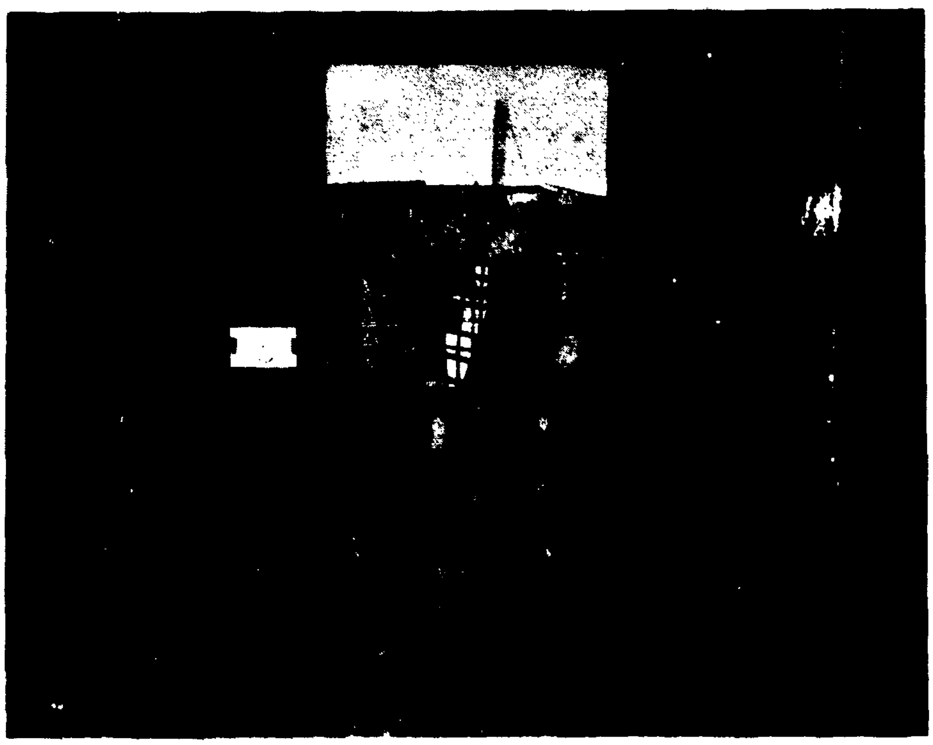

Fig. 10 EXAMPLE OF CONCRETE BREAK-UP

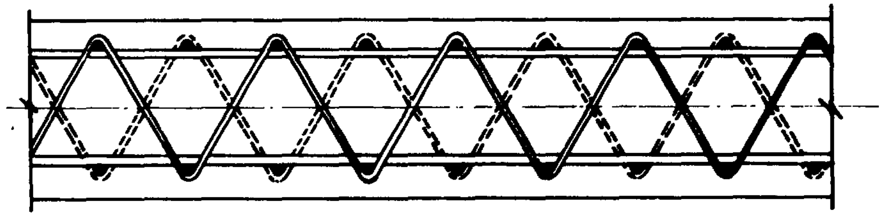

Fig. 11 NEW METHOD OF REINFORCEMENT USING LACING STEEL

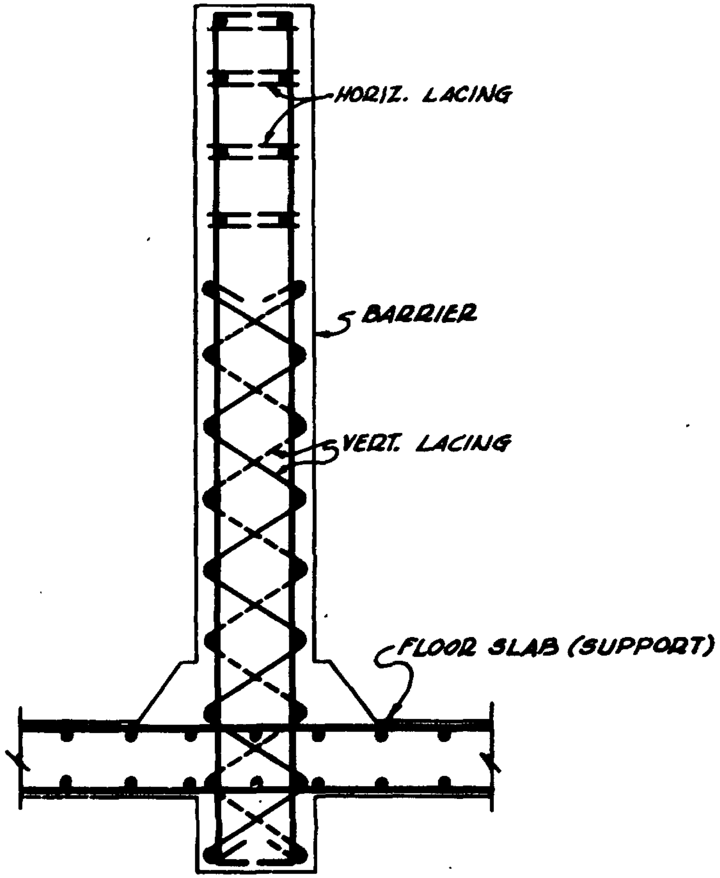

Fig. 12 TYPICAL WALL REINFORCEMENT

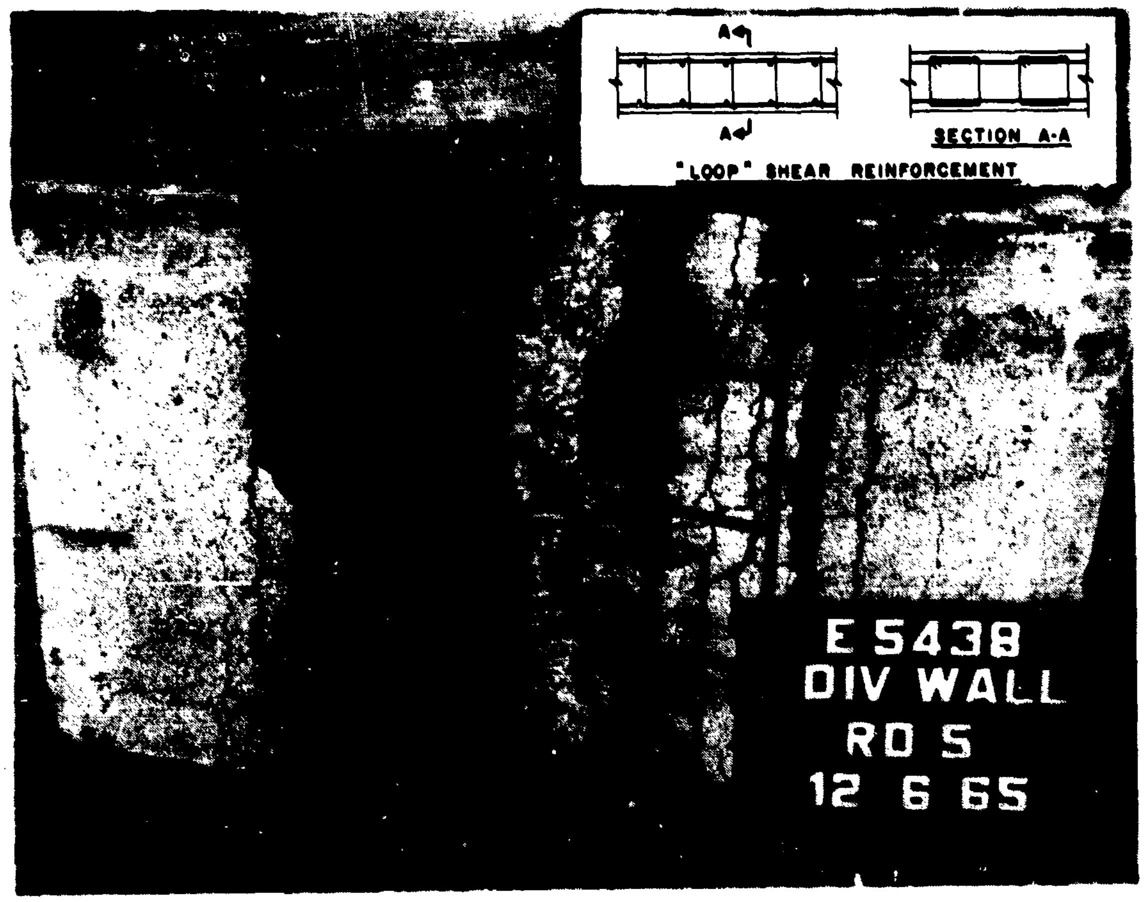

Fig. 13 TYPICAL PURE SHEAR FAILURE

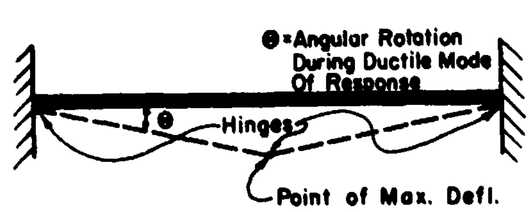

Fig. 14 FORMATION OF PLASTIC HINGES

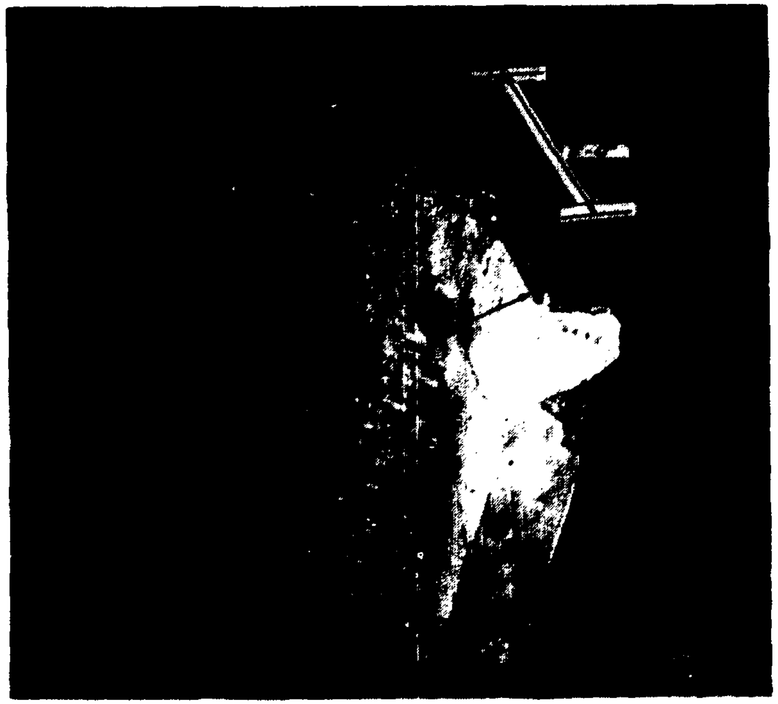

Fig. 15 TEST RESULTS OF REINFORCED CONCRETE SLAB

Fig. 16 TEST RESULTS OF COMPOSITE SLAB

Fig. 17 FAILURE AT PLASTIC HINGES OF LACED MEMBER

Fig. 18 BACKWALL FAILURE OF CUBICLE WITH LACED REINFORCEMENT

Fig. 19 PRE-SHOT VIEW OF 1/8 SCALE BAY STRUCTURE

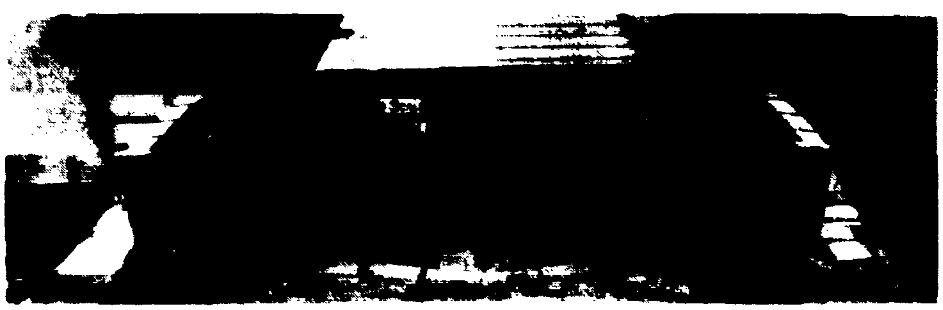

Fig. 20 POST-SHOT VIEW OF DONOR SURFACE OF BACKWALL
(1/8 SCALE BAY STRUCTURE)

Fig. 21 POST SHOT VIEW OF ACCEPTOR SURFACE OF BACKWALL
(1/8 SCALE BAY STRUCTURE)

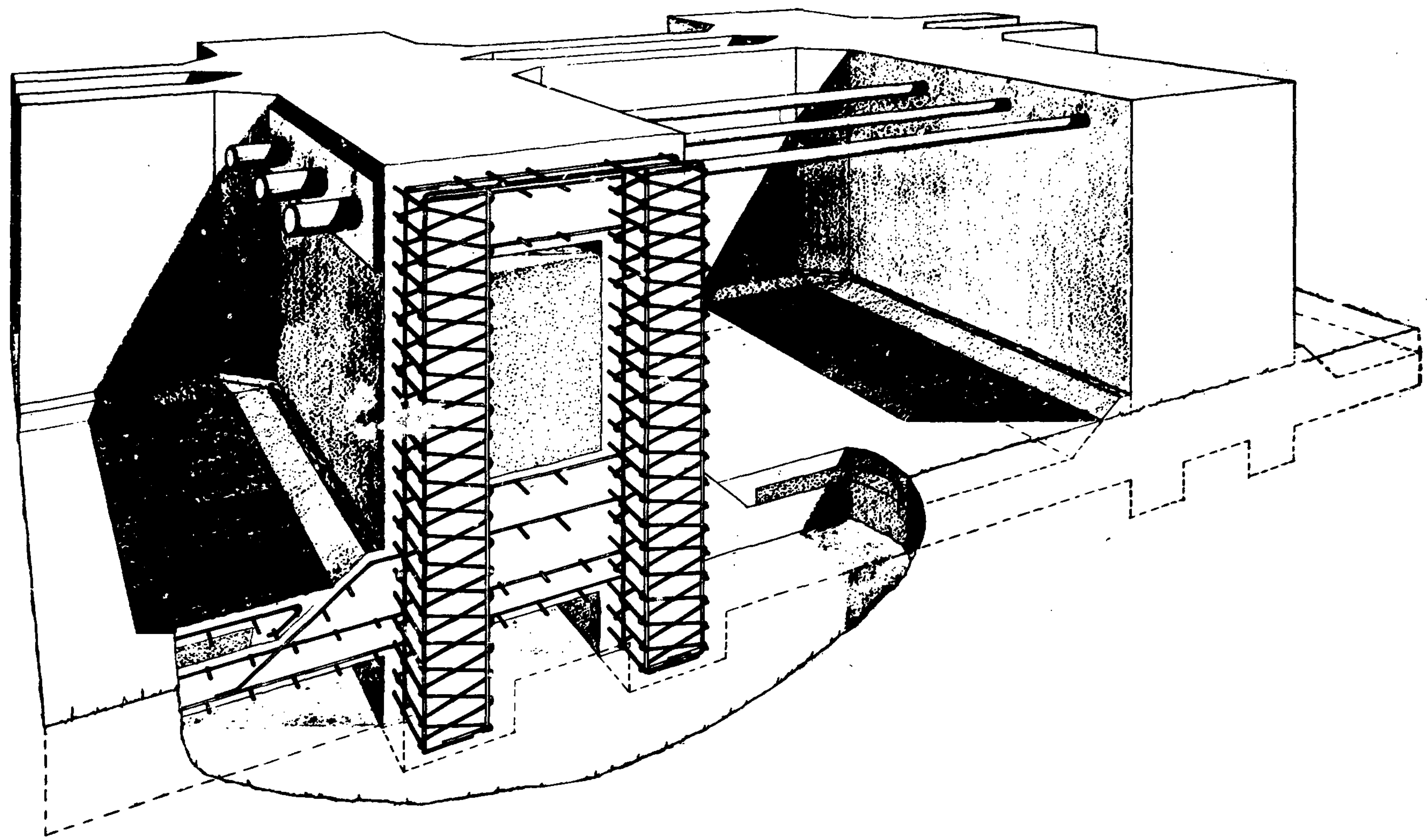

Fig.22 I/3 SCALE MODIFIED PHASE C-13 CUBICLE

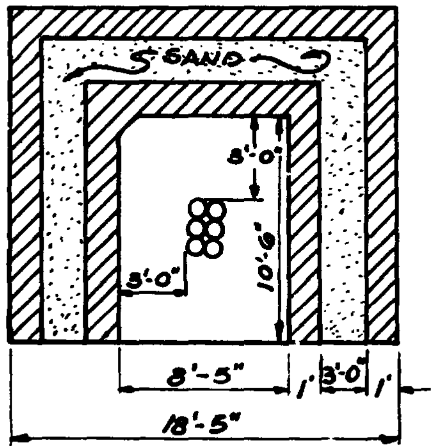

Fig. 23 PLAN OF FULL SCALE C-13 CUBICLE

Fig. 25 POST-SHOT DAMAGE TO FULL SCALE C-13 CUBICLE.

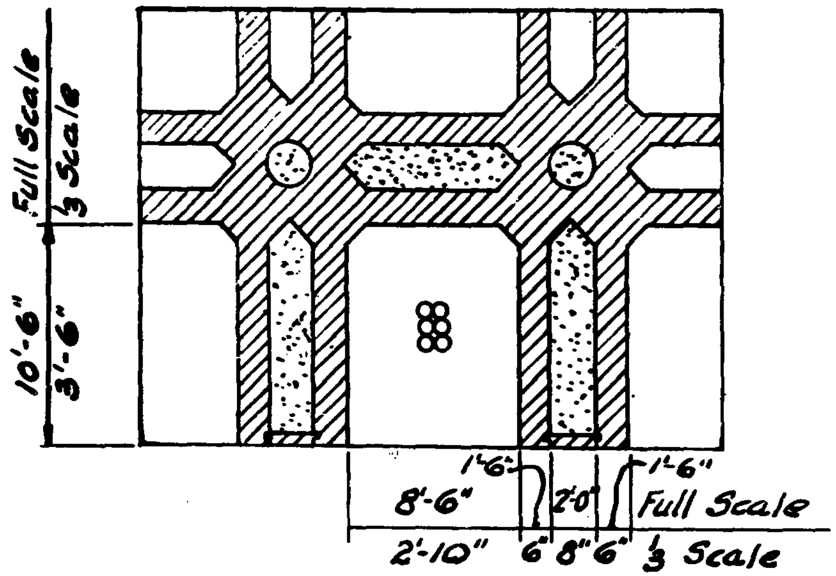

Fig. 24 PLAN OF 1/3 SCALE MODIFIED C-13 CUBICLE

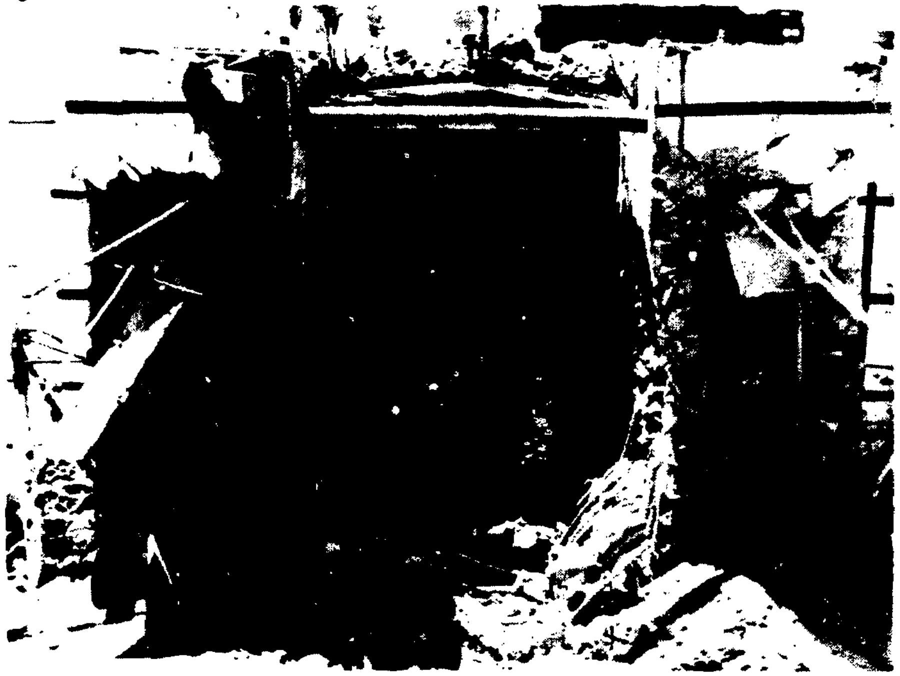

Fig. 26 POST-SHOT DAMAGE TO 1/3 SCALE MODIFIED C-13 CUBICLE

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THE USE OF FIBROUS CONCRETE IN MODEL STUDIES FOR PICATINNY ARSENAL

by

Wm. Roberts, OCE, Ohio River Division Labs.

1. Original work on the use of fibres in concrete was carried on by Dr. J. P. Romualdi at Carnegie Institute of Technology (1) and S. Goldfein at Ft. Belvoir, Virginia (2). An investigation of the use of randomly spaced fibres in portland cement concrete to produce a shatter resistant concrete was initiated at the Ohio River Division Laboratories in 1963 (3). During fiscal years 1965 and 1966 a program relating the use of fibrous concrete to the construction of explosive storage cubicles was conducted by the Laboratories under the sponsorship of the Picatinny Arsenal (4). A summary report of this work was presented by Gilbert Williamson at the Seventh Annual ASESB Seminar.(5) All of these studies showed that the inclusion of random fibres greatly improved the impact and shatter resistance of a concrete and reduced the velocity of those spalls which did occur.

2. Currently the ORD Laboratories are participating in the Picatinny Response Test No. 4 to the extent of fabricating eight one-third scale fibrous concrete test slabs. Four of the slabs will contain, in addition to random fibres, approximately two and three quarters percent steel reinforcing bars; the remaining four slabs slightly less than eight percent.

3. The concrete for all of the slabs will be made with a water-cement ratio of 0.45 by weight and will contain a 3/8-inch maximum size aggregate. Entrained air content will be maintained at 8 $\pm$ 1/2 percent which is normal when using this size coarse aggregate. Slump will be maintained at 5 inches to provide the necessary placeability. Using a Type III high early strength cement the 7 day compressive strength of the basic concrete will average slightly over 6000 psi. Fibre content of the concrete will be 1.75 percent of the absolute volume of the cement, sand, water and entrained air. The fibres are incorporated into the concrete during the latter part of the mixing process.

4. Two types of fibres are to be used in these slabs. One is nylon commercially described as "15 denier, Type 120, bright nylon fiber". The nylon is cut to 3/4-inch lengths and "opened" or fluffed. The material has the general appearance of absorbent cotton. The second fibre is a steel wire .017 inch in diameter with a shallow crimp every 1/4 inch and cut to a length of 1 to 1-1/4 inch. The wires have the appearance of those used in wire brushes.

5. During our initial work with fibres, non-air entrained concrete and many different types of fibres with lengths up to six inches were used. A great deal of difficulty was experienced in dispersing the longer fibres due to their tendency to ball up and it was finally found necessary to limit the fibre length to a maximum of 100 times the fiber diameter. It was also found that the cohesiveness of air entrained concrete aided in dispersal. The fibres in the present program present no dispersal problems in concrete having the properties described above.

6. Placement of fibrous concrete in non-reinforced sections involves no particular difficulty so long as the mix is in a cohesive, plastic state. The ease of placement in sections which are reinforced depends upon the quantity and spacing of the reinforcing bars and also the shape of the section. In all cases it is necessary that adequate equipment be available for vibration of the concrete as it is placed and that the rate of placement not exceed the capacity of the vibrators. The concrete must be initially placed very nearly in its final position as fibrous concrete cannot be flowed or carried by vibration.

7. At the present time an additional program is under discussion with Picatinny Arsenal personnel. This program will involve the fabrication of one or more one-eighth scale model storage cubicles. It is possible that the use of fibrous concrete will be included in this program.

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BLAST ATTENUATION STUDIES

IN DIVIDING WALL PROTECTIVE CONSTRUCTION

by

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ABSTRACT

This paper presents a summary of Blast Attenuation Studies conducted by the Waterways Experiment Station in support of studies by Picatinny Arsenal for the Dividing Wall program sponsored by the Armed Services Explosive Safety Board. The theoretical basis for materials selection is presented together with results of tests conducted to date.

BLAST ATTENUATION STUDIES

IN DIVIDING WALL PROTECTIVE CONSTRUCTION

INTRODUCTION

1. The ever-present possibilities for accidental detonations of explosives and high energy propellants in facilities for manufacture, maintenance, and storage of such materials pose a serious problem of reducing the blast effects on adjacent areas. The high shock pressures associated with a large explosion are sufficient to destroy conventional structures and to produce fragments of sufficient energy to cause propagation between adjacent bays of ammunition storage and processing complexes. Previous studies have established that high velocity fragments are a principal mechanism of propagation.

2. The experimental test program being conducted at the Waterways Experiment Station (WES) is designed to compare the effectiveness of various wall protection schemes in reducing the peak pressure transmitted to a final structural wall from an accidental explosion. Possible dissipative materials are selected on the basis of the waste-heat concept. The wall protection schemes are developed using both specially formulated dissipative materials and impedance mismatch configurations in an attempt to reduce the peak pressure transmitted to a final structural wall.

APPROACH

Theoretical

Waste Heat

3. The waste-heat concept embodies the principle that a portion of the energy of a shock wave is irreversibly lost in raising the temperature of the medium through which it propagates. This concept was first proposed by F. B. Porzel[1*] in 1957.

4. Shock wave energy may be partitioned into two main categories of kinetic and internal energy as shown in fig. 1. Energy at the shock front is partitioned equally into internal and kinetic, shown separated by the Rayleigh line connecting the initial and final shocked states. The waste-heat fraction is defined by the area bounded by the Rayleigh line and the Hugoniot of the respective material. This energy is evidenced as a temperature rise in the medium through which the shock wave propagates. Kinetic energy is due to the velocity imparted to the particles which subsequently becomes available through momentum transfer.

5. The hydrodynamic energy is due to compression of the medium and, subsequently, becomes available through expansion and continues to support a shock wave. This fraction may also be reduced using materials which exhibit a hysteresis effect in its loading and unloading stress-strain relationships; however, the strain energy associated with most distended materials should be low. Although it is highly compressible, air is a highly efficient transmitter of shock energy. The process is reversible and the hydrodynamic energy is returned to further support the shock.

* Raised numerals refer to similarly numbered items in the Literature Cited at the end of this report.

Also, both solids and liquids are efficient transmitters of shock energy in the pressure range of a few kilobars.

6. Idealized composites, as studied theoretically by M. A. Chasseyka[2], indicate that the waste-heat fraction can amount to as much as fifty percent of the total energy contained in the shock wave. This would require a vertical Rankine-Hugoniot (R-H) curve above the locking pressure for a material composed of a mixture containing appreciable amounts of entrained air. While this is not physically easy to accomplish, it can be approximated using materials which exhibit R-H curves such as shown in fig. 1. The R-H curve shown has not been experimentally determined in this pressure range for the materials tested; however, this relationship can be closely deduced through comparison with tests on similar distended materials.

7. A material consisting of a composite of air and solids takes advantage of the high compressibility and temperature rise of air under shock loading. During loading the air fraction will be compressed and the temperature rise quite high, whereas the solid fraction will barely decrease in volume and the temperature rise will be insignificant.

8. The heat transfer process at these elevated temperatures and pressures is very complex. The efficiency of this process is dependent on the temperature differential between the solid surface and the air. Also, the time available for this transition to occur is relatively short, being the same order of magnitude as the rise time of the pressure. It is assumed that, as the solid fraction crushes into the voids, the particles are pulverized and are mixed intimately with the air in such a way that the equilibrium temperature is reached within the period of the rise time of the

shock pressure. Despite the small mass of the air, the high temperature represents substantial energy. The reasons for limiting the air fraction are of a practical nature. If the air fraction is too high, then the composite behavior will approach that of air since the solid mass may not be sufficient to absorb the thermal energy, i.e., would be less efficient as a heat sink. Also, if the air temperature is high enough to cause vaporisation of the solids, then the expansion adiabat would be that of a gas.

9. Theoretical studies of blast effects in idealized composite materials and various soils have been conducted by M. A. Chasseyka and F. B. Porzel[3]. The results of their study indicate that a composite material containing 80 percent air and 20 percent solids by volume has a peak overpressure versus distance curve which decays as $\frac{1}{R^6}$. Composite mixtures containing equal proportions of air and solids show a pressure decay proportional to $\frac{1}{R^7}$. These values, when compared to the spherical divergence associated with air which is proportional to $\frac{1}{R^3}$, represent a substantial effect of entrained air on peak stress attenuation.

<u>Impedance Mismatch</u>

10. The second method of reducing blast pressures is by the use of laminated materials in which the laminae possess widely differing shock impedances. Fig. 2 shows the relationship between stress and particle velocity for three materials, solid concrete, cellular concrete, and foamed plastic. The behavior of a shock wave at an interface can be understood from a graphical representation provided the unloading path from a shocked state is known. It can be shown that the initial peak shock pressure can be substantially reduced through several

mismatch interactions. In this simplified analysis attenuation effects are not included; however, the effect would be to reduce the peak pressure further. Materials which possess the greatest mismatches are obviously the best choices for the laminate construction. The thickness of the laminae cannot be arbitrarily chosen since the reduction in pressure may be lost if reflections occur which "shock-up" the low impedance materials. These should be chosen on the basis of the expected pulse length and the velocity of propagation in the various laminates. The use of mismatch laminates following attenuating materials may prove to be a rational scheme since the shock pressure should drop off rapidly through the attenuating material, and there will be a trade-off point where any additional energy absorption may not be worth the higher reflected stress into the final structure. The higher reflected stress could be lowered through the use of materials with lower shock impedance when compressed. This is shown in fig. 2 using a foamed plastic.

11. Foamed plastics in locked states are believed to exhibit an R-H equation of state comparable to the solid material from which they are foamed. Therefore, the reflected P-U curve shown in fig. 2 is that of lucite. The stress imparted to the final wall is reduced to approximately one-half of that resulting from the use of cellular concrete as the final laminate.

Experimental

12. A series of tests was designed to study the effectiveness of various wall protection schemes in reducing the peak reflected stress imparted to a final wall. Various distended materials were tested in a configuration which has a reasonable similarity to small scale slab tests conducted by Picatinny Arsenal[4]. Protective construction of the sand-filled sandwich type has shown some promise in previous studies in the dividing wall program and is, therefore, used as a basis for comparison with other protection schemes.

13. The test configuration is shown in fig. 3. From practical considerations, the scale factor for these tests was selected to be 1/6. Full scale is taken to be a standard one-ft-thick dividing wall with a storage capacity of 270 lb of high explosive. It might also be noted that this corresponds to a scale factor of 1/2 for comparison with the 1/3 scale slab tests using 10 lb of composition "B" explosive.

14. As shown in fig. 3, the flight of a free surface pellet is photographed at 5000 frames/sec for which the velocity is computed. The aluminum acceptor plate is fitted with O-rings to prevent blow-by of the burning gasses which would obscure the flight of the pellet.

15. The method of Rhinehart[5] is used to provide a method of measurement of the peak stress produced by explosive loading. This method involves the measurement of the velocity imparted to a small pellet when placed on the free surface of an aluminum plate. Aluminum was chosen because its acoustic impedance is approximately that of concrete. The peak stress is related to the free surface velocity (V) of the pellet

as follows:

$$\sigma = \rho_0 C V/2$$

where:

ρ is the density, and

C is the acoustic velocity of the aluminum plate.

The absolute accuracy of this technique is contingent on a number of assumptions.

a. It is assumed that the incident compression pulse is of the shock type, i.e., that it has a very steep rising shock front.

b. It is assumed that the pressure profile of the rarefaction is identical to that of the incident compression at the instant it reaches the free surface.

Materials.

16. Previous investigation at WES of shock-absorbing materials in connection with hardened structures has produced cellular concretes with the following properties:

a. Density 20-40 lb/cu ft;

b. Air fraction 30-60 percent;

c. Static yield stress 50-500 psi.

The voids are evenly dispersed within a brittle matrix of hardened cement paste through the use of foaming agents. The density of these mixtures may be increased using higher density fillers. Expanded portland-cement grout has been proportioned with a density of 135 lb/cu ft and approximately 40 percent voids; however, the elastic yield stress is significantly higher. The physical properties for the materials tested

to date are shown in table 2. It also seems desirable that in order for a material to be truly dissipative it must also have high thermal conductivity. In order for the solid phase to subdivide or shatter under shock-loading and mix with the air phase, the voids should be small and evenly dispersed within a low strength brittle matrix. The indications are that this feature should facilitate the transfer of thermal energy.

17. An additional series of tests is planned for the following varieties of foamed sulfur samples as furnished by Southwest Research Institute.

a. Specimen No. 1: 23.9 lb/cu ft rigid sulfur foam.

b. Specimen No. 2: 21.9 lb/cu ft rigid sulfur foam.

c. Specimen No. 3: 15.1 lb/cu ft rigid sulfur foam.

d. Specimen No. 4: 14.2 lb/cu ft rigid sulfur foam.

e. Specimen No. 10: 38 lb/cu ft sulfur-vermiculite concrete.

f. Specimen No. 10: 38 lb/cu ft sulfur-vermiculite concrete.

g. Specimen No. 11: 48 lb/cu ft sulfur-vermiculite concrete.

h. Specimen No. 11: 48 lb/cu ft sulfur-vermiculite concrete.

Future tests will also include some polyurethane samples. These materials will be tested to determine both the dissipative characteristics and usefulness as low impedance materials to be used in laminate mismatch studies.

Results and Discussion

18. Several tests were repeated to check the reproducibility of the stress measurement. Due to the spherical geometry of the shock

front and the propagation path through dissimilar materials, a direct peak stress measurement is questionable. However, for a relative indication of the peak stress in the present configuration, the free-surface-pellet technique appears to be valid to within ± 5 percent. The results of tests conducted to date are shown in table 1. The first four tests were conducted for check-out purposes on camera timing, alignment, and method of pellet placement.

19. The velocity pellets were held in place with a thin oil film between hand-lapped surfaces. Both surfaces of the pellet and plate were lapped before each shot. Bond of this type provided an interface essentially transparent to the incident compressive pulse and opaque to the reflected rarefaction pulse. The bond strength, being only a few psi, should have a negligible effect on the free surface velocity since separation will occur for a very low, net, tensile stress.

20. Rounds No. 5 and 6 were conducted to establish the peak reflected stress from an unprotected wall at a Z distance of 0.5 The peak stress of 31,300 psi correlates closely with theoretical predictions[5]. Rounds 7 and 8 established the peak stress at a Z distance of 0.8 to be approximately one-half that measured at a Z distance of 0.5. This is expected since the air-shock pressure is diminished through geometric dispersion by close to the same amount. A total thickness of 6 in. of aluminum was used in Round No. 9 consisting of three 2-in. plates. The Z distance measured to the near surface of the donor plate was 0.5, while the final acceptor plate was at a Z distance of 0.8 for a comparison with Rounds 7 and 8. This shot shows that the stress reduction

through four inches of aluminum is comparable to the same thickness of air, with only geometric dispersion being significant. The results of 7, 8, and 9 show the reproducibility of the tests to be within the accuracy expected.

21. A model of the sand-filled sandwich protection scheme was tested in Rounds 10, 11, and 12. The transmitted stress was not reduced through the use of 2 in. of sand. The particle size of the sand was centered around a sieve size No. 50, similar to the sieve analysis for previous studies conducted by Picatinny Arsenal.

22. Rounds 7-12 give a standard of comparison for all attenuating materials and configurations to be tested which is approximately 47.5 ft/sec at 14,550 psi.

23. Rounds 13 and 15 were of the sandwich type using 2 in. of cellular concrete Mix No. 1, as listed in table No. 2. These results indicate a stress reduction of approximately 25 percent.

24. Cellular concrete Mix No. 2 was tested in Round No. 16. The test configuration was again of the sandwich type. Although only one test has been completed on this material, the stress measurement was slightly lower than Rounds 13 and 15, indicating approximately 35 percent stress reduction in addition to the geometric dispersion as measured in the standard tests.

25. Rounds 17, 18, and 19 were tests on cellular concrete and expanded concrete; however, the test configuration consisted of 4 in. of the test material and a 2-in. acceptor plate. Rounds 17 and 18 were at a Z distance of 0.5 to the near surface of the concrete (for comparison with Rounds 7-13) and consisted of Mixes No. 3 and 1, respectively.

Round 19 was cellular concrete Mix No. 4 at a Z distance of 0.5 to the near surface of the aluminum plate for comparison with Rounds 5-6. Round 17, highest density mix tested, showed nearly a 20 percent reduction of stress. Round 18, having the lowest density, indicated no reduction, while Round 19, with material having a density three times higher and void ratio of one-half as much as Round 18, produced nearly 20 percent reduction.

Conclusions

26. From the limited number of tests conducted to date, the conclusions which can be deduced with reasonable certainty are limited. The first phase of this study was conducted in an exploratory manner, and the data thus generated should be regarded as such.

27. The method of test appears to be adequate for a comparison of dissipative materials and various protection schemes. Pellet velocities and computed pressures correlate closely with those predicted from theoretical computations of reflected pressures.

28. The tests of the sand-filled sandwich-type configuration, using sand as a filler material, has shown no reduction in peak stress. All cellular concrete mixtures proportioned for this study have indicated a reduction of 20-35 percent in peak stress transmitted to the acceptor plate. Mixture No. 1, having the lowest density, lowest yield strength, and highest void fraction, has been less effective as a dissipative material. Mixture No. 2, which has a higher density and a significantly higher yield stress, has shown greater stress reduction despite

the smaller void fraction. Additional tests are needed on these materials; however, the implications are that a higher density with similar compressive strength and void ratio as Mixture No. 1 is desirable. Exposing these materials to a higher stress level did not yield greater stress reduction as shown in Rounds 17 through 19. Round No. 18 indicates an even higher reflected stress than when no wall protection material was used. This result does not seem reasonable when compared to Rounds 17 and 19 on similar materials. Additional tests are needed on this material before an explanation can be attempted.

Literature Cited

1. Porzel, F. B., Design Evaluation of BER (Boiling Experimental Reactor) in Regard to Internal Explosions. Armour Research Foundation of Illinois Institute of Technology, Report No. ANL-5651, 1957.

2. Chasseyka, M. A., Studies of Surface and Underground Nuclear Explosions. ARF Project No. 4195, Final Report, 1961.

3. Chasseyka, M. A., and Porzel, F. B., Study of Blast Effects in Soil. ARF Project No. D119, 1958.

4. Supporting Studies to Establish Safety Design Criteria for Storage and Processing of Explosive Materials. Quarterly Report No. 14, Picatinny Arsenal, 1966.

5. Granstrom, Sune A., "Loading characteristics of air blasts from detonating charges," Transactions of the Royal Institute of Technology, Stockholm, Sweden, 1956.

6. Rhinehart, J. S., "Scabbing of metals under explosive attack: multiple scabbing," J Appl Phys, 23, p 1229, November 1952.

TABLE 1

SUMMARY OF RESULTS

Round No.	Sample Composition: Donor Pl.	Sample Composition: Test Material	Sample Composition: Acceptor Pl.	Z Distance $X/W^{1/3}$ *	Z Distance $X/W^{1/3}$ **	Pellet Velocity ft/sec (avg)	Peak Stress psi (avg)
5, 6			2 in. AL.	0.50	0.50	102 ± 5	31,300
19		4 in. Mix No. 4	2 in. AL.	0.10	0.50	84	25,700
9	2 in. AL.	2 in. AL.	2 in. AL.	0.50	0.81	50	15,300
7, 8			2 in. AL.	0.81	0.81	48 ± 1	14,700
10, 11, 12	2 in. AL.	2 in. Sand	2 in. AL.	0.50	0.81	48 ± 2	14,700
13, 15	2 in. AL.	2 in. Mix No. 1	2 in. AL.	0.50	0.81	37 ± 1	11,300
16	2 in. AL.	2 in. Mix No. 2	2 in. AL.	0.50	0.81	31	9,500
17		4 in. Mix No. 3	2 in. AL.	0.50	0.81	39	11,900
18		4 in. Mix No. 1	2 in. AL.	0.50	0.81	65	19,900

* Z Distance measured to surface of sample nearest charge.
** Z Distance measured to surface of acceptor plate.
± Values represent maximum scatter in data.

Table 2

Mixture No. 1

Cellular Concrete (1 cu ft)

Cement	11.4 lb
Water	10.0 lb
Mearlcrete foaming time	6.8 sec
Density (plastic)	22 lb/cu ft
Density (dry)	20 lb/cu ft
Compressive strength	70 psi
Air fraction	60 %

Mixture No. 2

Cellular Concrete (1 cu ft)

Cement	21.6 lb
Water	18.5 lb
Mearlcrete foaming time	5 sec
Density (plastic)	40 lb/cu ft
Density (dry)	30 lb/cu ft
Compressive strength	350 psi
Air fraction	45 %

Mixture No. 3

Expanded Cement Grout (1 cu ft)

Cement	47.6 lb
Water	23.8 lb
-50 Ilmenite sand	101.4 lb
Aquagel	1.27 lb
TIC	0.76 lb
Aluminum powder AP 3xD	2.03 g
Air-entraining agent	101.4 ml
Density (plastic)	175 lb/cu ft
Density (dry)	135 lb/cu ft
Compressive strength	3000 psi
Air fraction	38 %

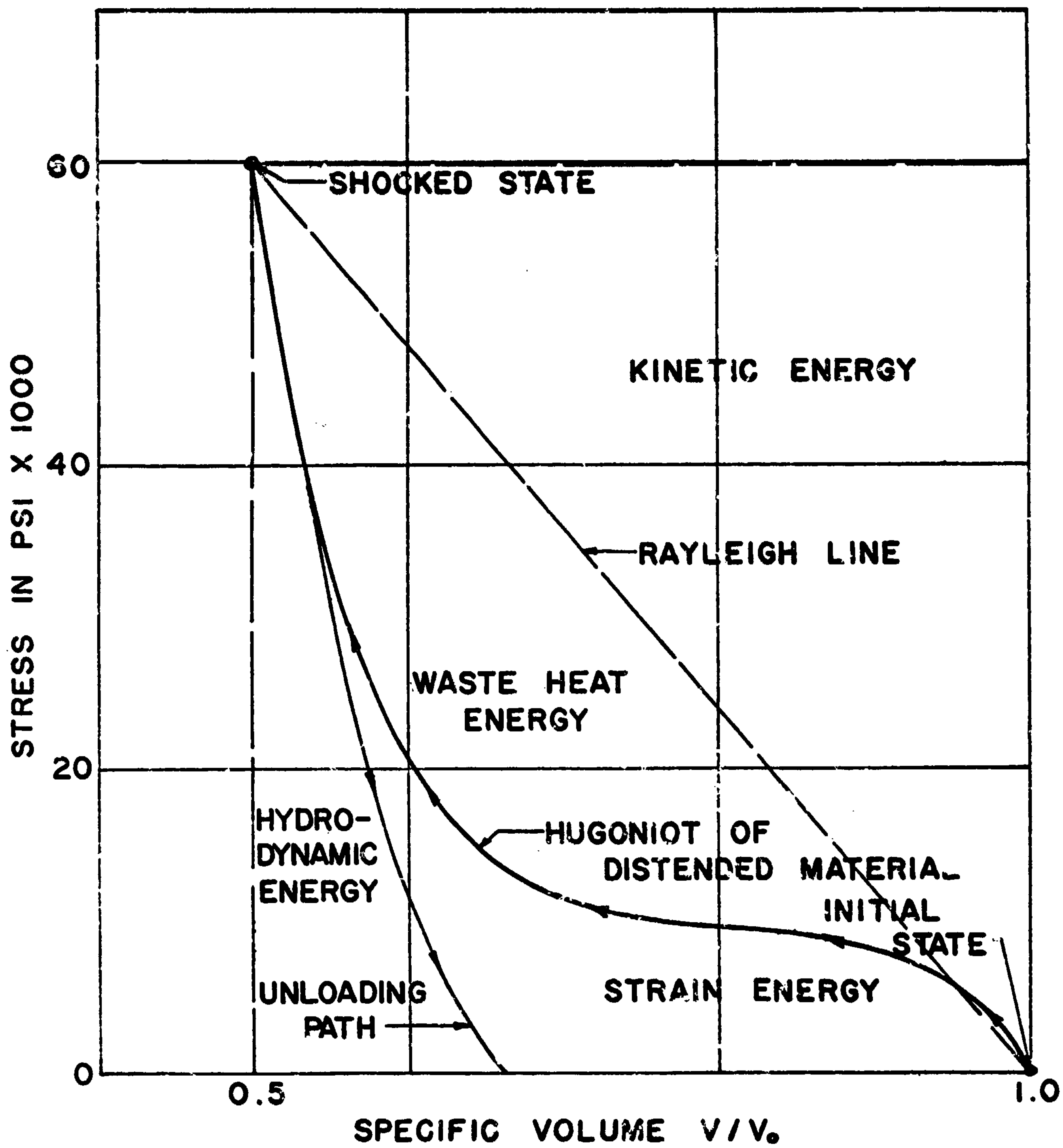
(Continued)

Table 2 (Continued)

Mixture No. 4

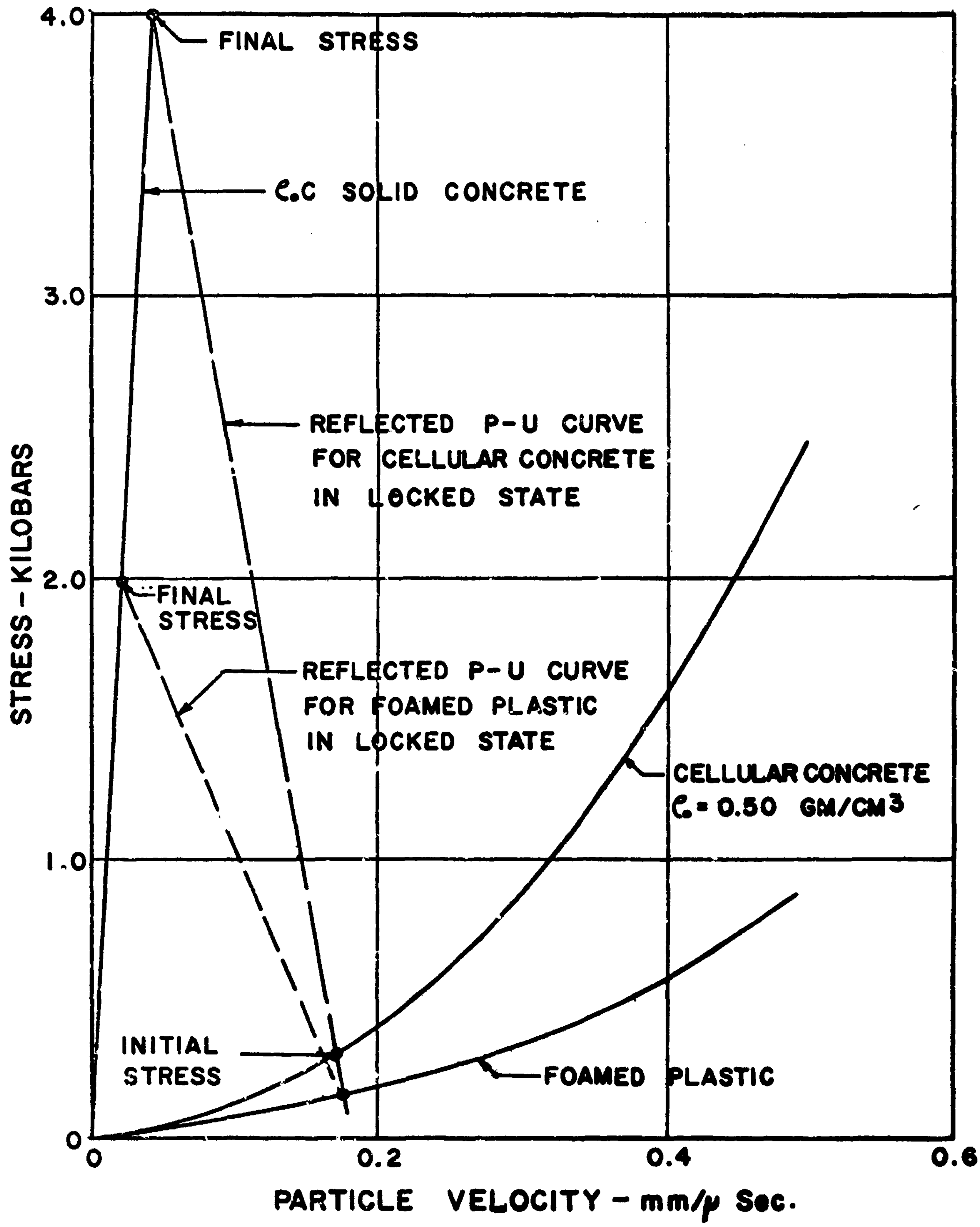
Cellular Concrete with Sand (1 cu ft)

Cement	14.7	lb
Water	11.4	lb
Mearlcrete foaming time	8.4	sec
-80 Ilmenite sand	40.2	lb
Density (plastic)	67	lb/cu ft
Density (dry)	62	lb/cu ft
Compressive strength	90	psi
Air fraction	45	%



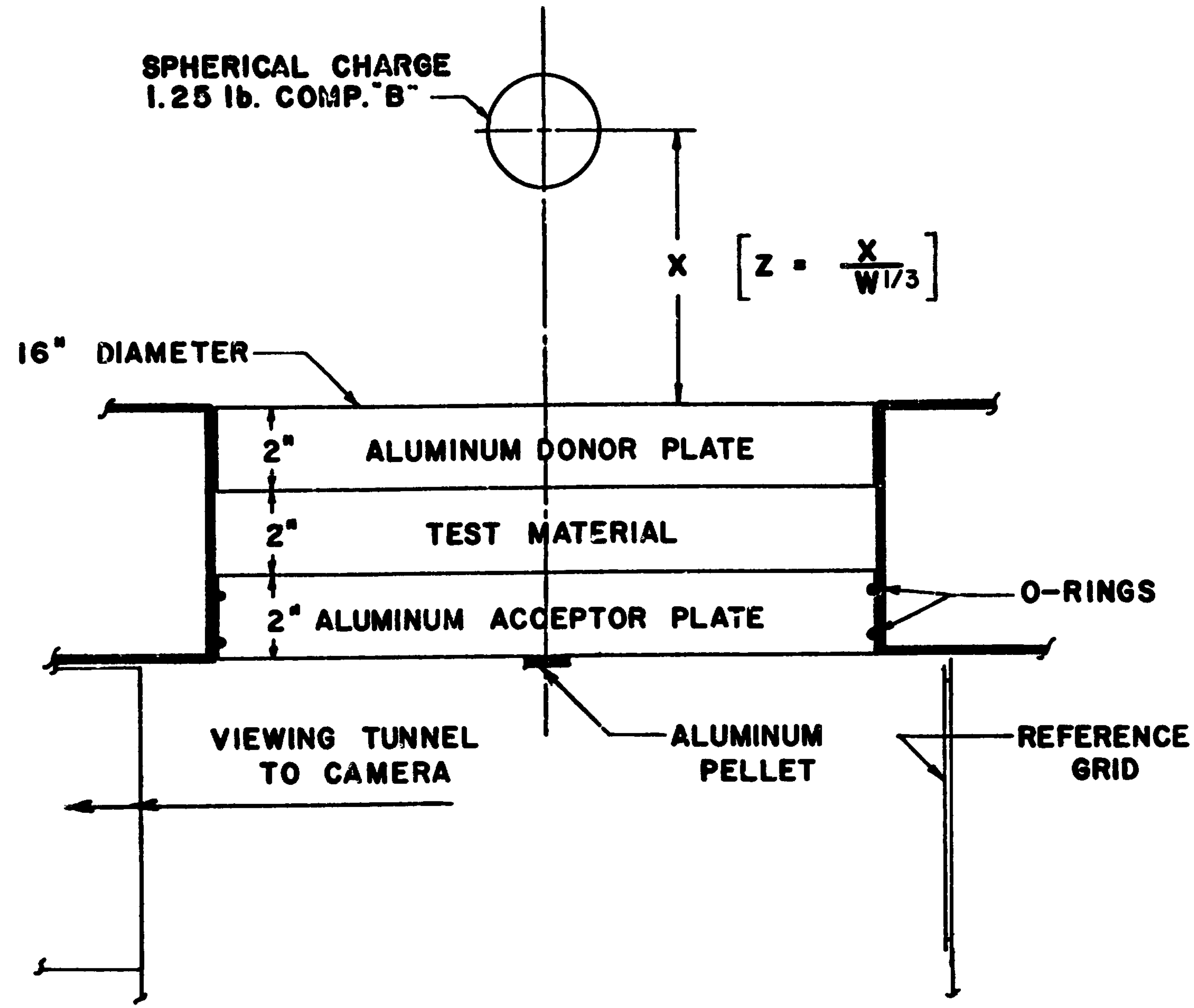
ENERGY PARTITIONING

Fig. 1



STRESS Vs. PARTICLE VELOCITY

Fig. 2



TEST CONFIGURATION

Fig. 3

Testing of Designs

S. Wachtell
Picatinny Arsenal

Testing of designs of high capacity reinforced concrete walls was generally done on scaled model slabs of the designs in question. Because of the extremely high cost of full scale testing, most of our work was done on $\frac{1}{3}$ scale model slabs. After screening of the various designs developed, it would then be practical to build full scale models at various check points on the way when quantitative data on the ultimate designs are required.

Testing Procedures

Testing of concrete slab designs was done at both the Naval Ordnance Test Station (NOTS) and Picatinny Arsenal. Full scale and one-third scale tests were done at NOTS while smaller scale tests were run at Picatinny Arsenal.

Two types of facilities were used at NOTS. The tunnel facility which is described in Reference 1 and a new versatile test facility which is described in Reference 2. The capacity of the tunnel facility is limited to about 30 lbs of explosive. When larger charges were used the tunnel started to collapse and required constant rebuilding. Therefore, design of higher capacity test stand was undertaken. Figure 2 shows a $\frac{1}{3}$ scale model slab ready for test in the tunnel facility with the explosive charge suspended. The steel plates at the sides can also be turned 90° to form the sides of a cubicle if that type of test data is desired. Figures 3, 4, and 5 show slabs being tested in the new versatile facility. This test stand can be modified to take slabs with spans of 2 feet to $7\frac{1}{2}$ feet in a vertical or

horizontal configuration. It has a capacity of up to 500 lbs of explosive. Figure 3 shows a $\frac{1}{2}$ scale slab with 2 foot span being tested in open configuration. Figure 4 shows a cubicle configuration with the slab as the backwall. Figure 5 shows a composite slab being tested as the sidewall of a cubicle.

The Picatinny test facility is similar to the NOTS tunnel but designed for testing 1/5, 1/8 and 1/10 scale slabs in vertical or horizontal position. The maximum explosive capacity is 8 lbs. The Picatinny facility was also extended to provide for testing of cubicle or bay type of structures with explosive capacity up to 20 lbs. Figure 6 shows this facility.

In using these test facilities it has been found that many factors affect the test results. Among these factors are (1) the shape of the explosive charge, (2) the support condition of the test slab, (3) the position (vertical or horizontal) of the test slab. In general the more rigid the support conditions with other conditions held constant, the more damage can be expected to a slab.

In order to simulate such conditions as would exist in a rigid structure such as a manufacturing bay or cubicle, provision was made in the new test facility for firmly bolting the test slabs to the test stand.

Examples of results obtained with the test slabs are shown in Figure 7. Details of some of the slab test data are reported in Reference 3. Additional work is being reported as it is completed.

References:

1. L. M. Patton & D. P. Ankeney <u>Test of Camera Technique for Obtaining Wall Fragment Velocity Data</u>
Naval Ordnance Test Station TP3522 May 1964

2. E. Cohen, N. Dobbs & R. Rindner <u>Description and Utilization of a Versatile Slab-Support Test Facility</u> Prepared by Picatinny Arsenal and

Ammann & Whitney under contract DA-28-017-AMC-423(A) to be published.

3. E. Cohen & N. Dobbs Summary of One-Third Scale Reinforced Concrete Slab Tests-Interim Report No. 1. Prepared for Picatinny Arsenal by Ammann & Whitney under Contract DA-28-017-AMC-423(A) June 1965

TEST SET-UPS 1/3 SCALE SLAB RESPONSE TEST SERIES 3

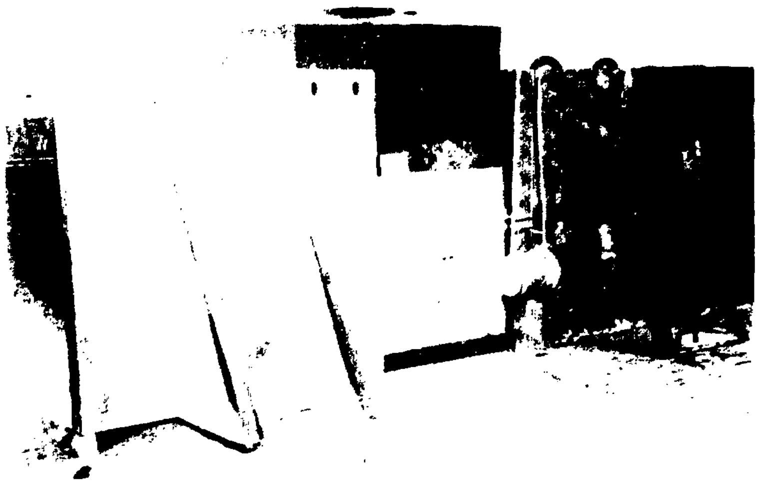


FIGURE 2 TEST SET-UP IN THE TUNNEL ARRANGEMENT

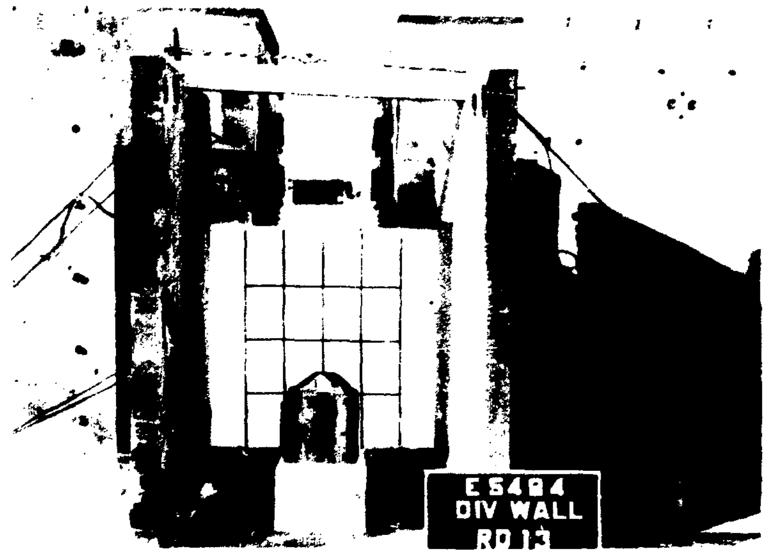


FIGURE 4 TEST SET-UP. SLAB SIMULATING BACKWALL

FIGURE 3 TEST SET-UP (NEW TEST FACILITY)

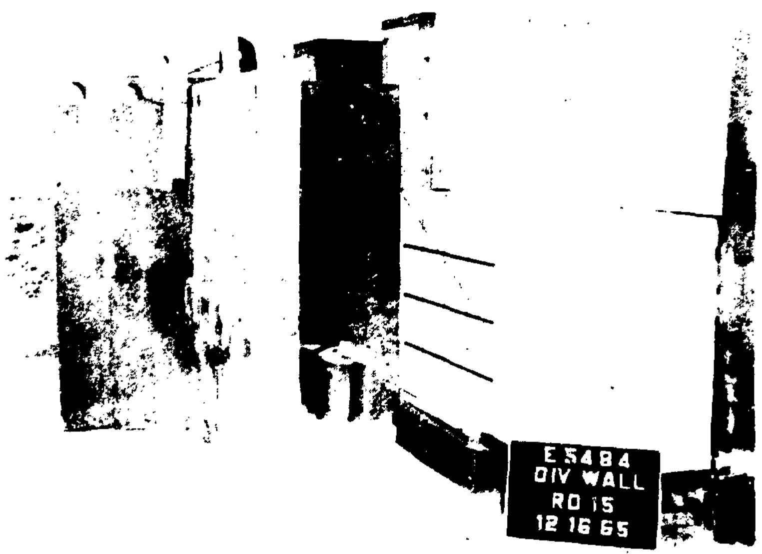


FIGURE 5 TEST SET-UP, SLAB SIMULATING SIDE WALL

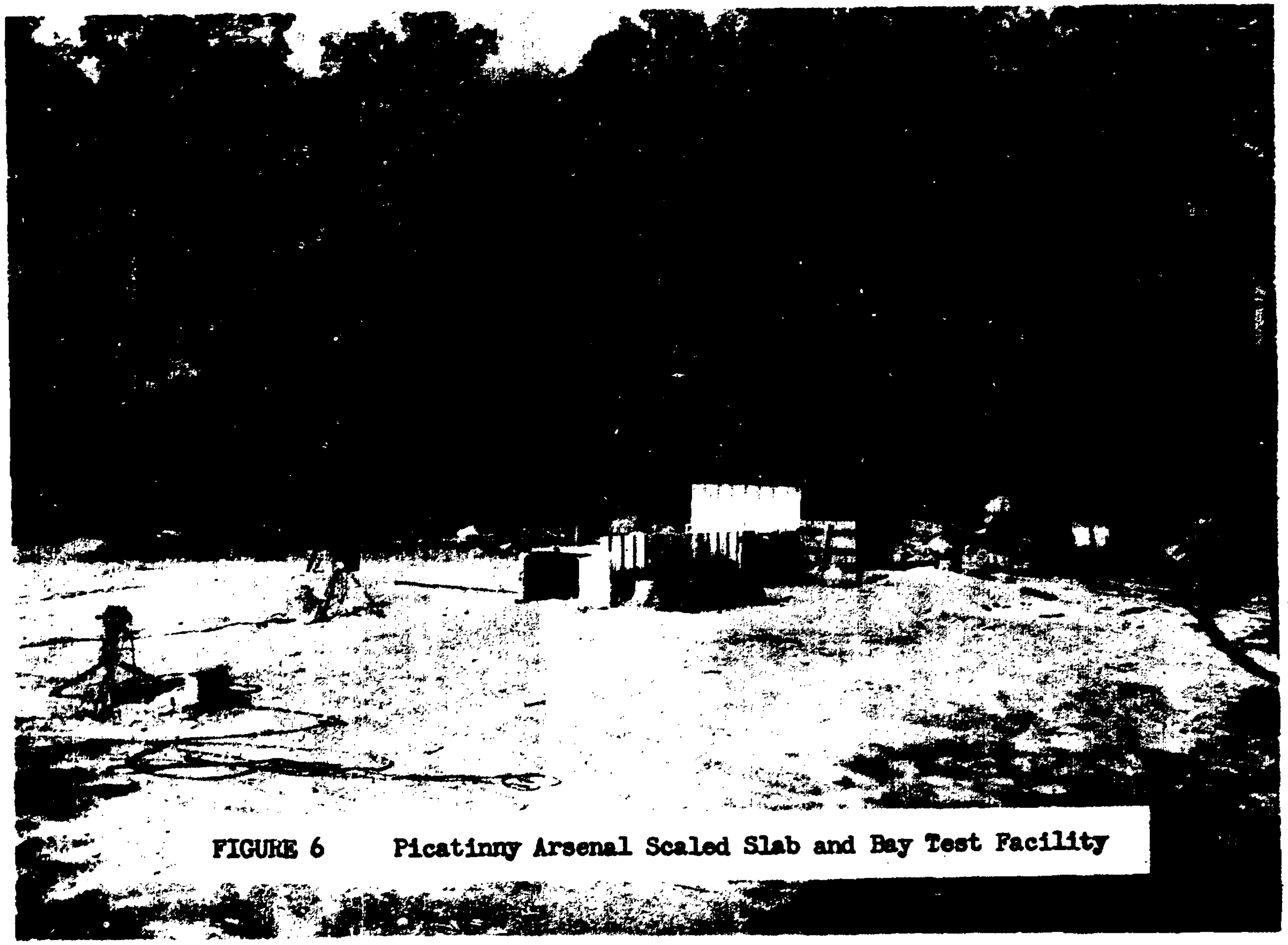


FIGURE 6 Picatinny Arsenal Scaled Slab and Bay Test Facility

1/3 SCALE SLAB RESPONSE TEST SERIES 3

ROUND 9 (ACCEPTOR SIDE)
Z = 0.42 W = 60 LBS.

ROUND 11 (ACCEPTOR SIDE)
Z = 0.5 W = 30 LBS.

ROUND 10 Z = 0.5 W = 40 LBS.

ROUND 12 (DONOR PANEL)
Z = 0.5 W = 60 LBS.

FIGURE 7

Studies to Validate Scaled Testing

S. Wachtell
Picatinny Arsenal

The use of scaled model testing to develop data for full scale design has always been the subject of dispute. However, when the purpose of a structure is to partially withstand destruction by blast from an explosion which may never occur, the cost of full scale testing will exceed the cost of the final structure. Thus, it becomes esseniial that less expensive model testing procedures be developed.

At the suggestion of Mr. R. G. Perkins of the ASESB, we undertook a program which we felt would demonstrate to what extent scaled model testing could be utilized to predict full scale response.

The program followed was to (1) to make a series of tests of carefully scaled models of prototype slabs using a series of scaling factors and (2) to prepare a prototype bay structure 20 feet deep, 40 feet wide and 10 feet high having a capacity of 2000 lbs of explosives and test both scaled models of this structure and a full scale model.

The majority of this program has been completed and is reported here.

Scaled Slab Test Results

An extensive series of slabs which had been tested on ⅓ scale were selected for testing at 1/5 scale, 1/8 scale and 1/10 scale. These slabs represent a wide range of capacities and include some composite types. A complete report of this data will be published when the tests are complete. Since the 1/5 scale work has not been completed, a comparison is shown of some typical 1/3, 1/8 and 1/10 scale tests. Figures 1, 2, 3, and 4 show

comparative results. In general, the extent of damage to each slab of one type is similar on all 3 scales. However, note that in figures 2 and 3 the extent of damage to the 1/10 scale slabs appears to be somewhat less than the 1/8 and 1/3 scale. We feel that this can be attributed to the inherent errors of the procedure which become more significant as the model size decreases. For example in the tests shown in Figure 2, the distance of the charge to the slab for the 1/3 scale test is 18.6 in. while for the 1/10 scale it is 5.4 in. An error in charge placement of 1/8" in the 1/10 scale test would have much greater effect than in the 1/3 scale test. In addition, in model construction itself, placement of the reinforcing and maintaining the ratio of cross section areas of reinforcing and concrete becomes increasingly difficult as the model size decreases. Probably the best balance of cost and testing accuracy exists in the vicinity of 1/8 scale model testing.

Included in our slab test work will be a comparison of results from static loading data as compared with dynamic loading. This is important for future design calculation.

Scaled and Full Scale Bay Test Results

The bay test series from 1/10 scale to full scale prototype for the originally calculated 2000 lbs capacity has been completed.

Figure 5 shows an artists rendition of a full scale prototype of the bay structure complex. Note that the construction is of a composite structure with walls comprising 2 feet of reinforced concrete - 4 feet of sand and 2 feet of concrete. Figure 6 gives a typical cross section of the wall showing some of the important features of the reinforcing patterns used. The main reinforcing bars are tied by vertical and horizontal shear reinforcement to permit the reinforcing bars to develop their full tensile strength under

load. This shear reinforcement is only placed at areas where maximum stress is developed. The bottom of the wall is reinforced at the floor slab by haunches and a tie beam pedestal. This is to allow for the high shear stress at the joint between the floor and the wall. The entire wall of the bay is monolithic with the floor slab to retain its structural integrity under stress. The tensile capacity of the wall is designed to be approximately equal to the shear capacity at the joints. The lip is intended to give better ground contact and footing and prevent rotation of the side wall. The central floor slab is thinned down to reduce mass and construction costs. The walls contain about 0.65% of reinforcing on each face.

Figure 7 shows some of the reinforcing during construction of the $\frac{1}{3}$ and 1/10 scale bay structures.

A detailed report showing the complete testing of the 1/10 scale model with details of design calculation and the rationale of the structure design is given in Reference 1.

The original test set ups and the results are shown in Figures 8, 9, 10 and 11. After completion of the 2000 lbs equivalent charge weight tests each of the test bays was in such good condition, (only minor damage to the outer wall) that additional larger charges were used. Figures 12, and 13 show the results after a 3000 lbs equivalent charge weight was detonated in the 1/3, 1/5, 1/8 and 1/10 scale bays. Note in Figure 12 that the 1/10 scale models shows a wide crack developing at the bottom center of the outside wall and base slab. This is probably due to the poor ground support provided for this bay, since it was manufactured in a model shop and transported to the test site. The bay was then placed on a bed of sand which was compacted as well as possible. However, there was still sufficient give to the

ground to allow a beam action to occur along the bottom of the center wall which caused the base to crack. This crack led to complete failure of the bay when tested at the next step with a 5000 lbs equivalent charge weight. The 1/3 and 1/5 scale bays were constructed on site on solid ground. This completely eliminated the problem. The 1/8 scale bay which was also transported to the test site was placed on a thin bed of sand which had a lean mix of sand and concrete below it to give a more solid base. This substantially reduced the base cracking and allowed the bay to maintain its strength for the subsequent 5000 lbs test shot.

Figures 14 and 15 show the results obtained with the 5000 lbs equivalent charge weight. The 1/10 scale bay failed completely while the 1/8 and 1/5 scale bays are at incipient failure. The 1/3 scale bay shows less damage than the others because the explosive capacity of the area was limited and only a 3000 lbs equivalent charge weight could be used. This was moved closer to the center wall in an attempt to simulate the same blast condition that would be obtained from a 5000 lbs charge. However, the damage here was naturally less than for the other scaled structures.

Since the 1/8 scale bay was still in reasonably usable condition after the 5000 lbs equivalent test, an additional test was made with 7500 lbs equivalent weight of explosives. This resulted in complete destruction of the center wall of the bay and produced fragments for the first time. The fragment velocity was about 100 feet per second. The appearance of this bay is shown in the upper part of Figure 16.

The lower part of Figure 16 shows damage to a new 1/10 scale bay with the same construction as the original, tested with 10,000 lbs equivalent weight of explosive on the first test. This bay was completely destroyed and produced fragments of about 150 feet per second.

The full scale bay will be subjected to the 3000 lbs and 5000 lbs tests in the near future.

Conclusions:

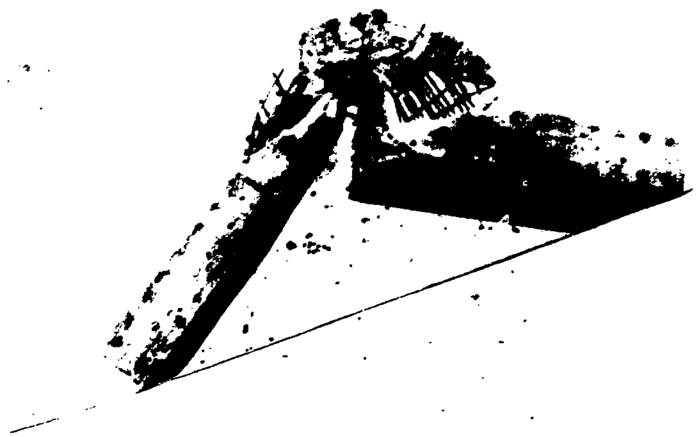
The results of this test program have thus far shown that scaled testing of concrete bays and slabs can be used to predict the capacity of full scale structures. The most practical scale for model testing is 1/3 to 1/8 scale.

The capacity of the bay structure is in the order of 7500 lbs of high explosive for prevention of propagation to acceptors weapons.
If personnel or material protection is needed then the capacity is appreciably lower.

Reference: 1. A. Schwarts, E. Cohen and N. Dobbs Picatinny Arsenal Technical Report Test of 1/10 Scale Bay Structure; Report #6 Supporting Studies to Establish Design Criteria for Storage and Processing of Explosive Materials July 1966

COMPARISON OF 1/8, 1/10 AND 1/3 SCALE SLAB TEST RESULTS

1/8 SCALE SLAB, ROUND 8
Z = 0.50 W = 0.93 LB.



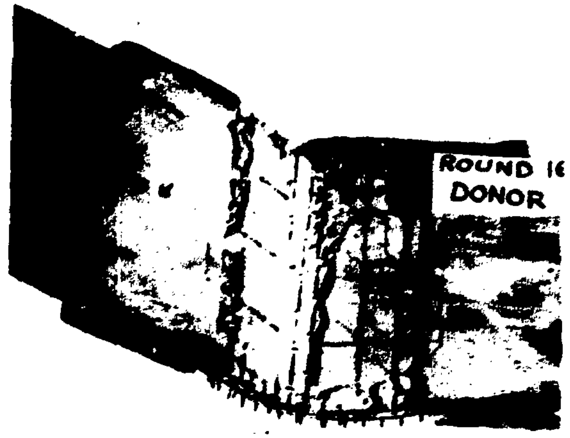
1/10 SCALE SLAB, ROUND 11
Z = 0.50 W = 0.53 LB.

1/3 SCALE SLAB, ROUND 6-1
Z = 0.50 W = 20 LBS.

FIGURE 1

COMPARISON OF 1/8, 1/10 AND 1/3 SCALE SLAB TEST RESULTS

1/8 SCALE SLAB, ROUND 3
Z = 0.50   W = 0.98 LB.

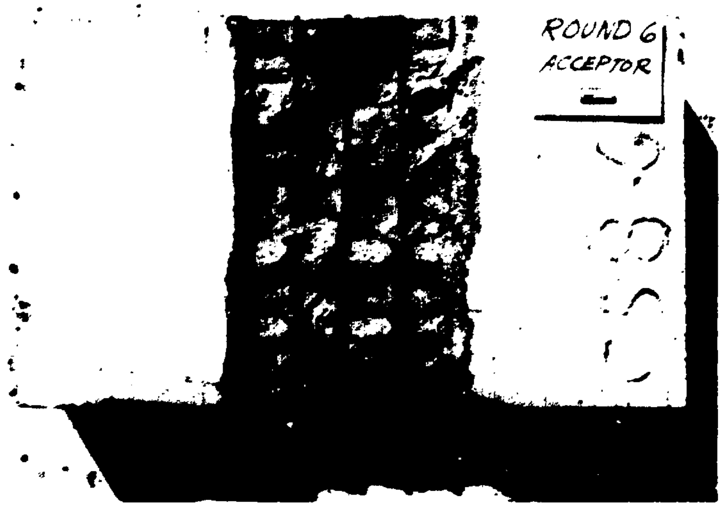


1/10 SCALE SLAB, ROUND 16
Z = 0.50   W = 0.53 LB.

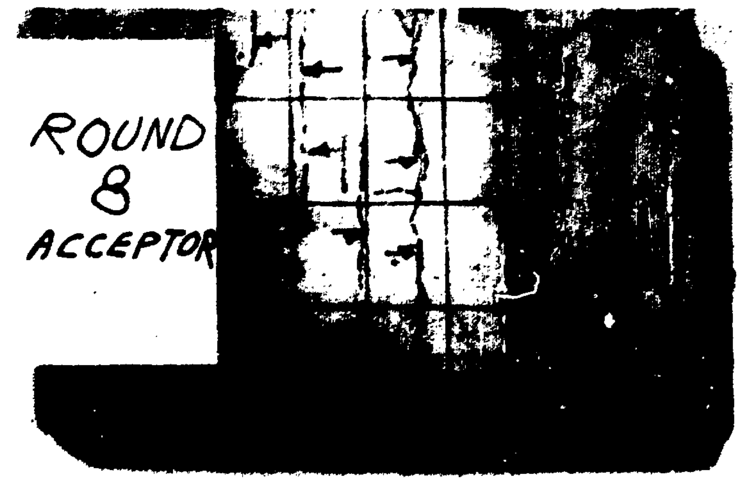
1/3 SCALE SLAB, ROUND 9-1
Z = 0.50   W = 20 LBS.

FIGURE 2

COMPARISON OF 1/8, 1/10 AND 1/3 SCALE SLAB TEST RESULTS



1/8 SCALE SLAB, ROUND 6
Z = 0.50 W = 1.59 LBS.

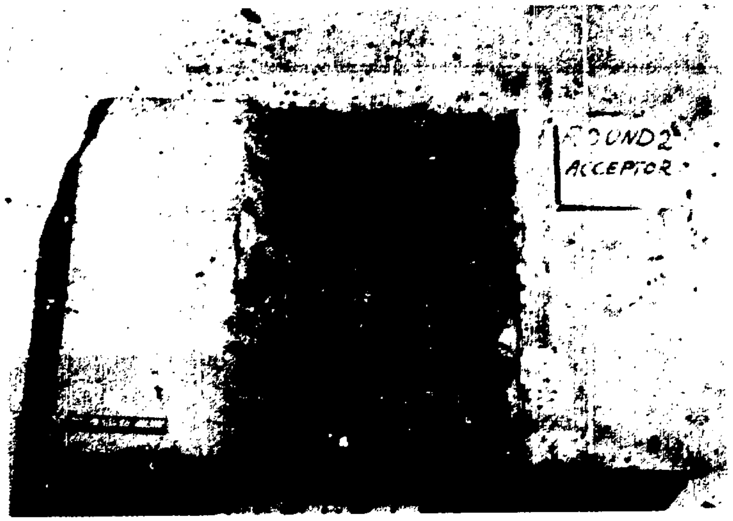


1/10 SCALE SLAB, ROUND 8
Z = 0.50 W = 0.81 LB.

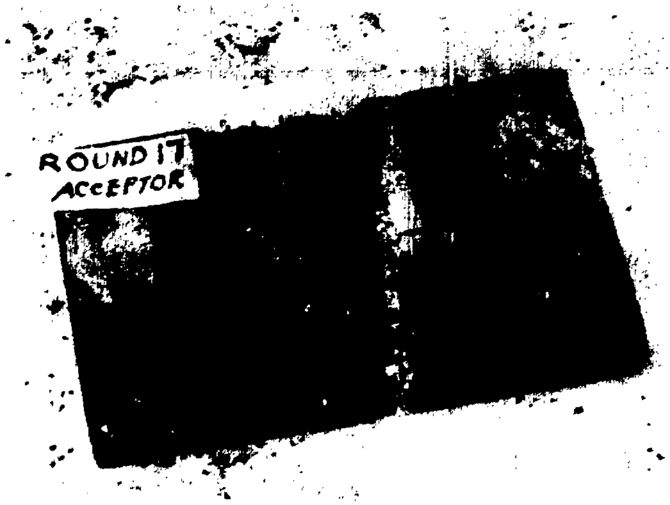
1/3 SCALE SLAB, ROUND 11-1
Z = 0.50 W = 30 LBS.

FIGURE 3

COMPARISON OF 1/8, 1/10 AND 1/3 SCALE SLAB TEST RESULTS



1/8 SCALE SLAB, ROUND 2
Z = 0.50 W = 1.60 LBS.



1/10 SCALE SLAB, ROUND 17
Z = 0.50 W = 0.81 LB.

1/3 SCALE SLAB, ROUND 7
Z = 0.50 W = 30 LBS.

FIGURE 4

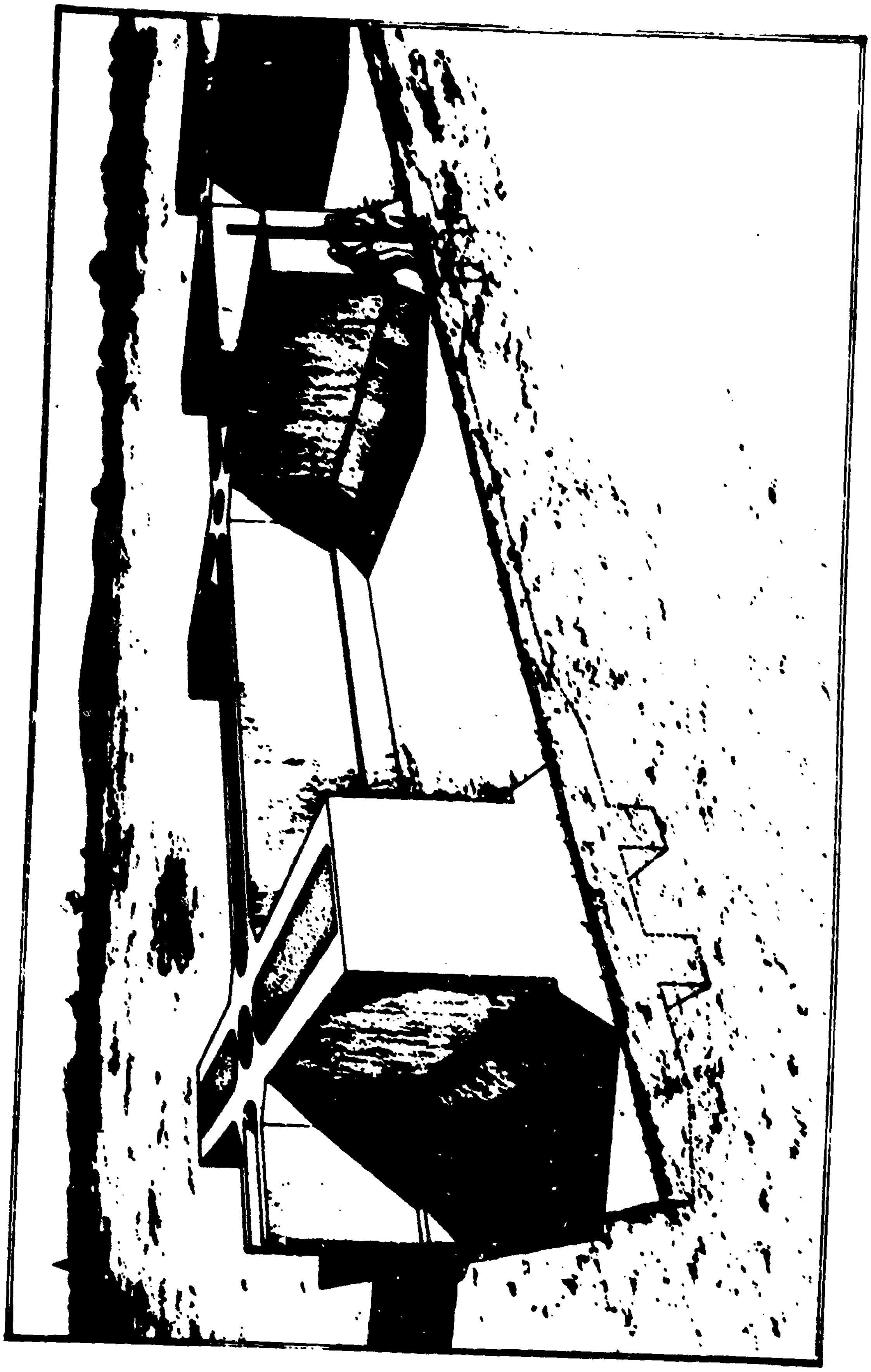


FIGURE 5 PROTOTYPE OF BAY STRUCTURE

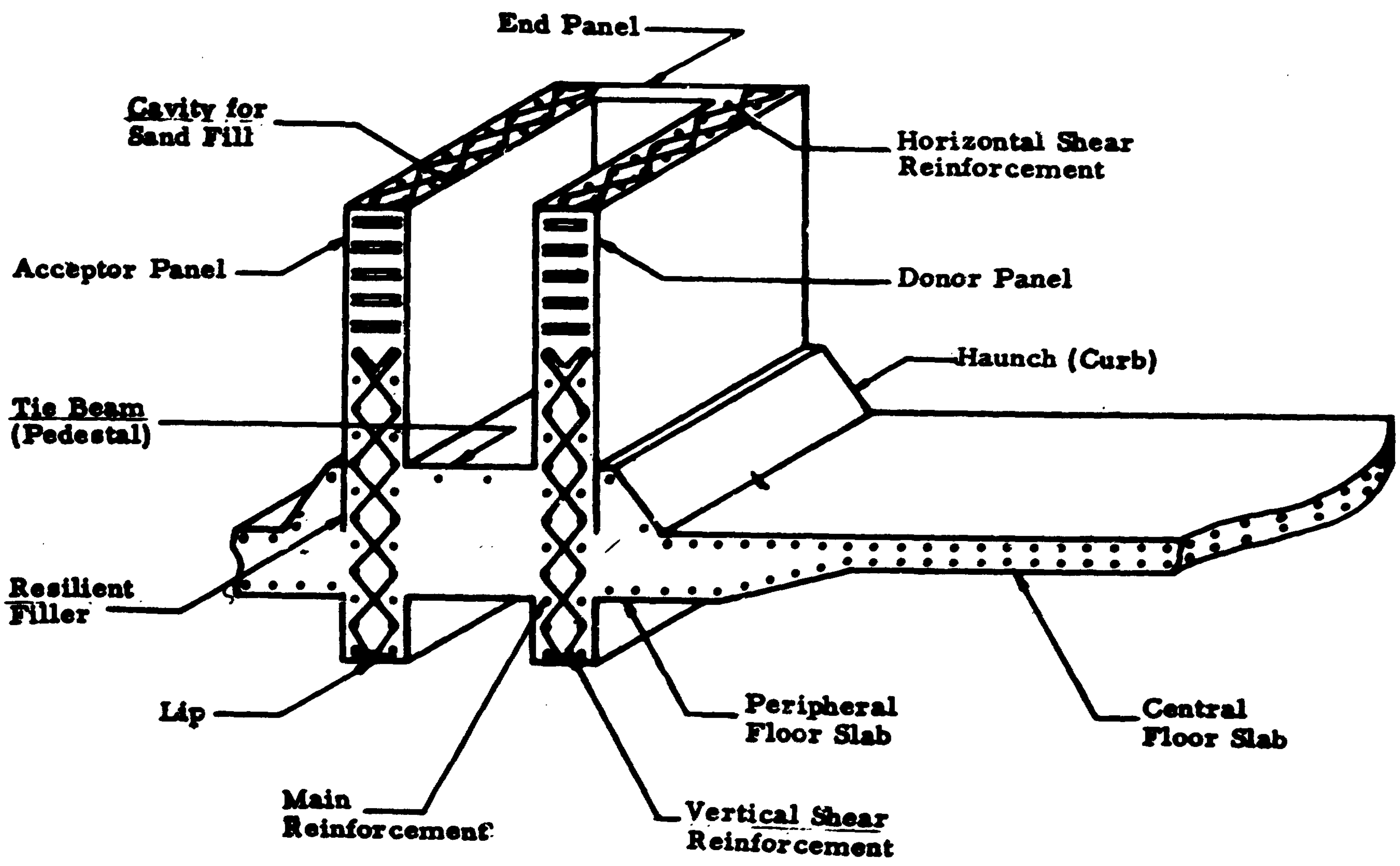
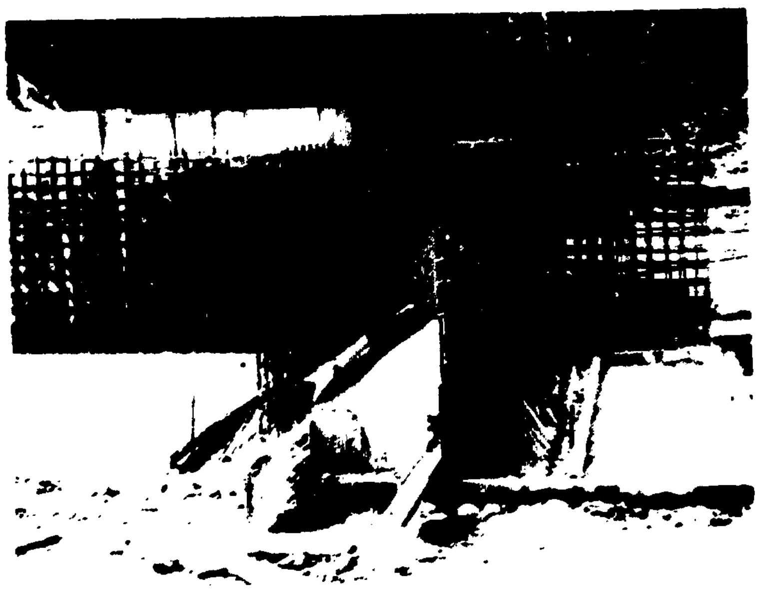
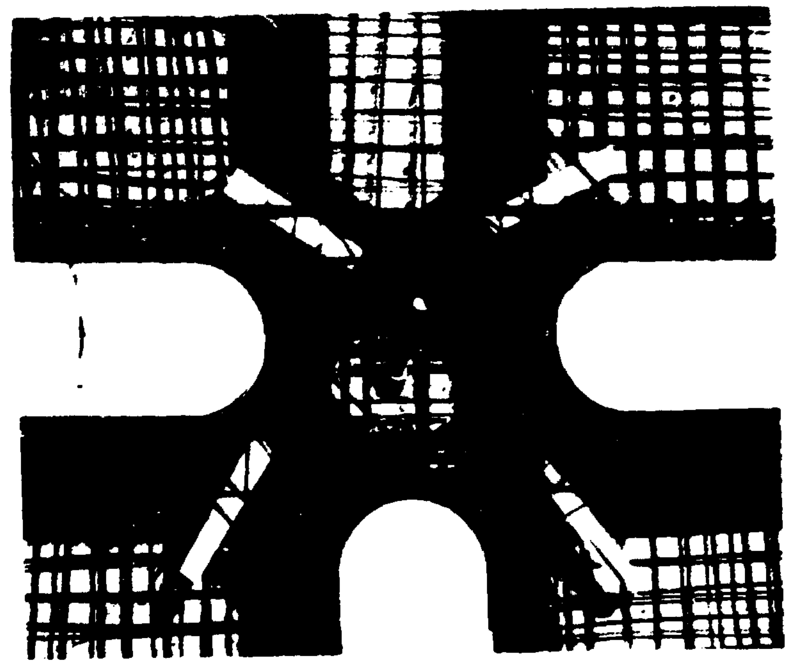


FIGURE 6 TYPICAL WALL AND FLOOR SECTION
BAY STRUCTURE

REINFORCING PATTERNS FOR TEST BAY



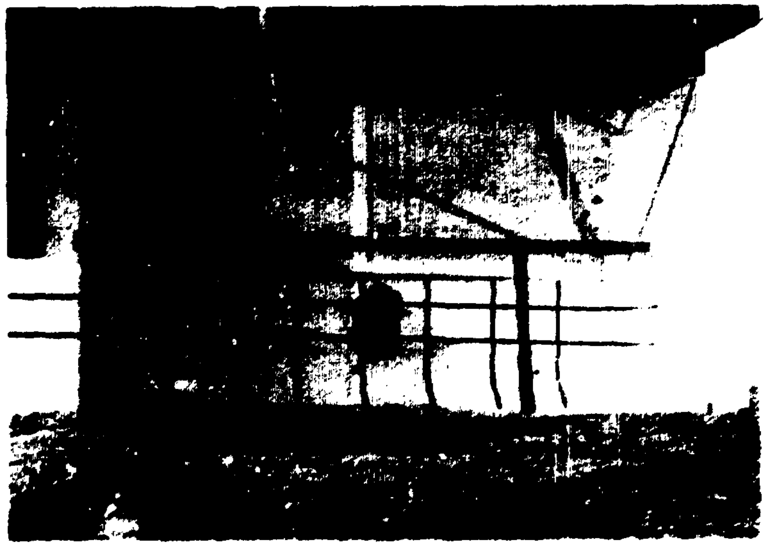
1/3 SCALE MODEL REINFORCING AFTER POURING OF MONOLITHIC FLOOR SLAB AND PEDESTAL. SHOWS ATTACHMENT OF WALL TO FLOOR SLAB AND PEDESTAL.



DETAIL OF 1/10 SCALE BAY REINFORCING SHOWING CORNER FILLETS AND STIRRUPS FOR FULL DEVELOPMENT OF TENSION REINFORCEMENT

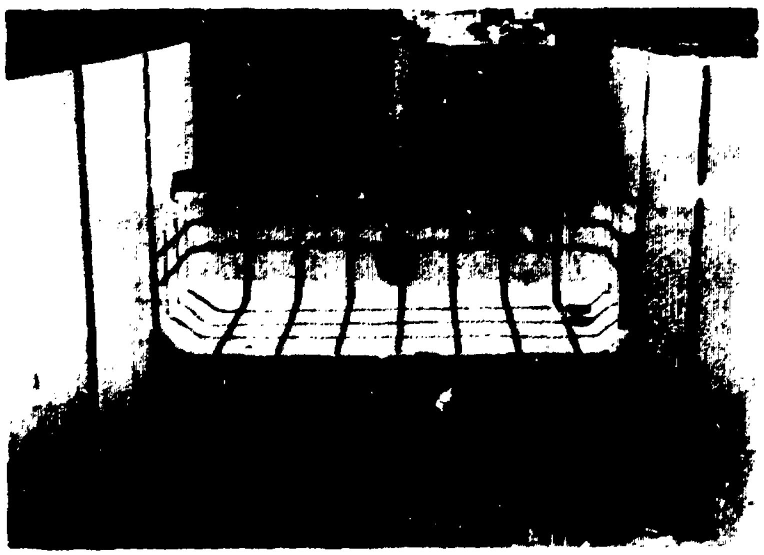
FIGURE 7

SCALED BAY TEST SET-UPS

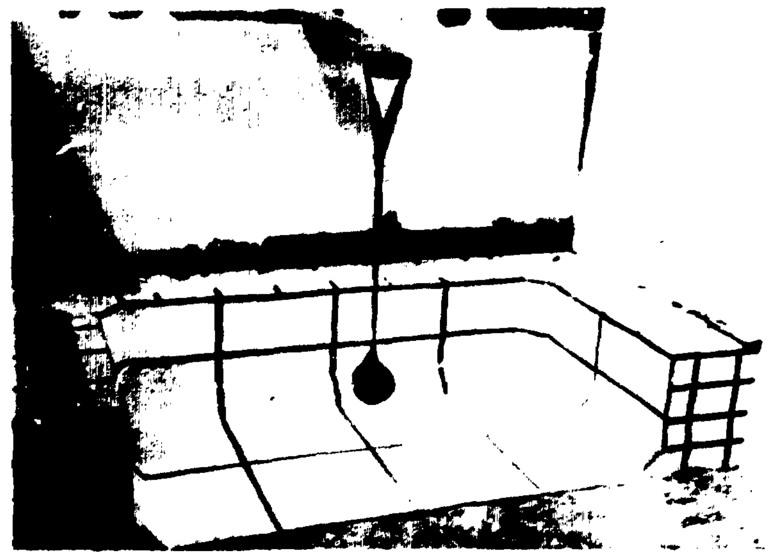


TEST SET-UP 1/3 SCALE BAY

TEST SET-UP 1/8 SCALE BAY



TEST SET-UP 1/5 SCALE BAY

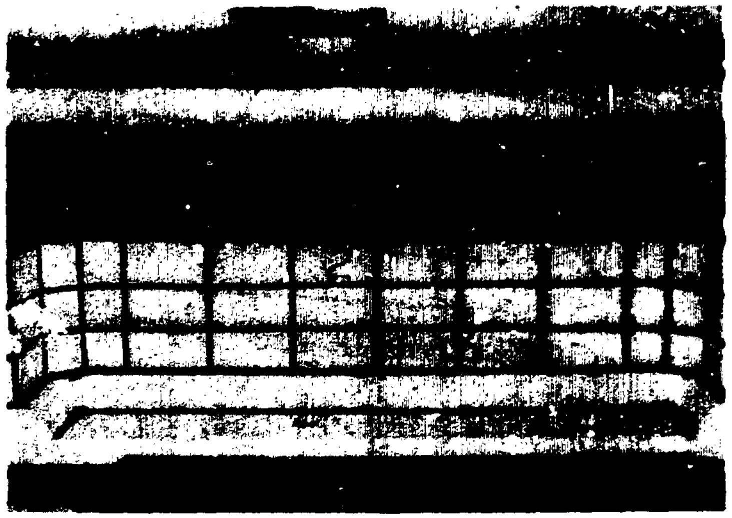


TEST SET-UP 1/10 SCALE BAY

FIGURE 8

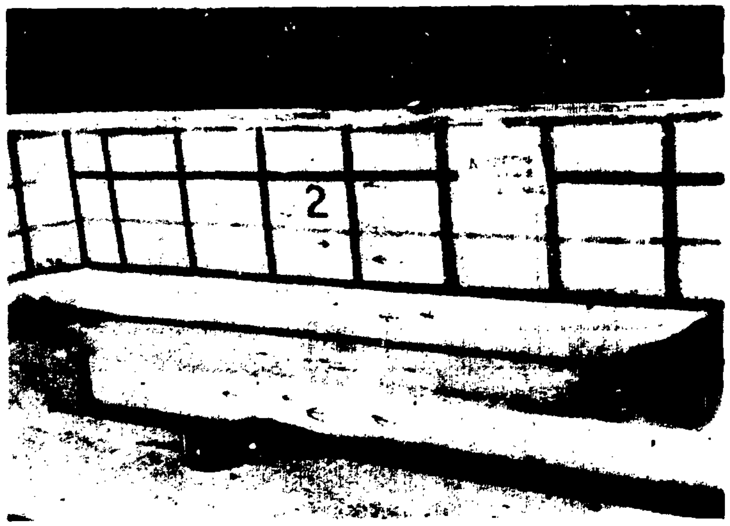
SCALED BAY TESTS ROUND 1 (2,000 LBS. HE EQUIVALENT)
CENTER WALL, ACCEPTOR SIDE

1/3 SCALE BAY Z = 0.775 W = 75 LBS.



1/8 SCALE BAY Z = 0.79 W = 4.0 LBS.

1/5 SCALE BAY Z = 0.785 W = 16 LBS.



1/10 SCALE BAY Z = 0.8 W = 2.0 LBS.

FIGURE 9

SCALED BAY TESTS ROUND 1 (2,000 LBS. HE EQUIVALENT)
DONOR SIDE

1/3 SCALE BAY
Z = 0.775, W = 75 LBS.

1/8 SCALE BAY
Z = 0.79, W = 4.0 LBS.

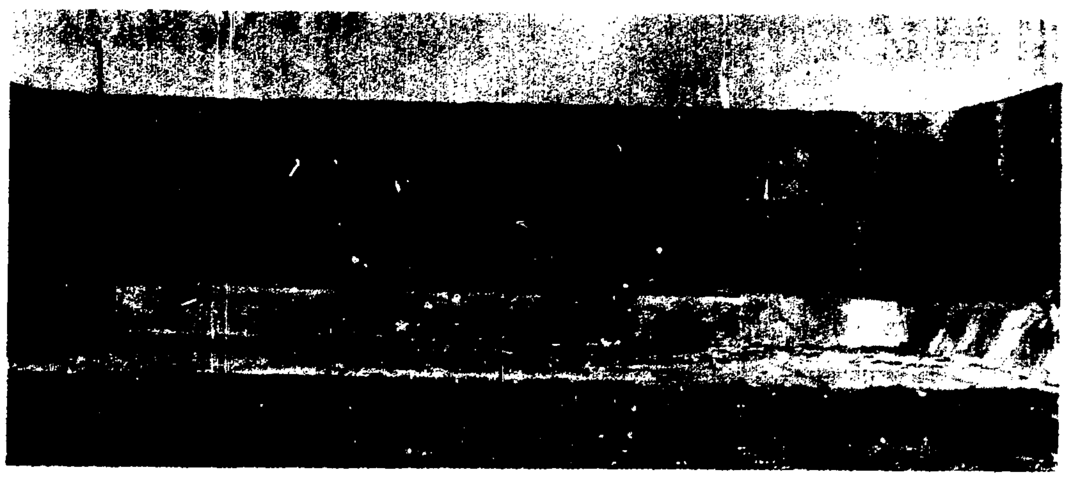
1/5 SCALE BAY
Z = 0.785, W = 16 LBS.

1/10 SCALE BAY
Z = 0.8, W = 2.0 LBS.

FIGURE 10

FULL SCALE BAY TEST - 2000 LBS. OF HIGH EXPLOSIVE

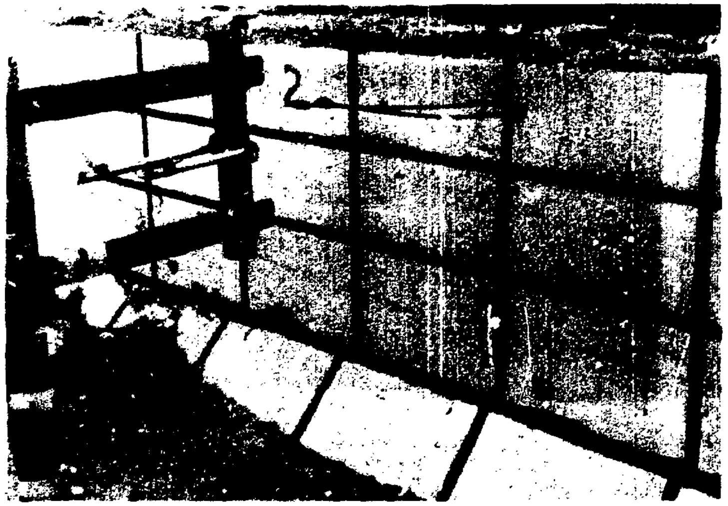
TEST SET-UP SHOWING 2000 LB SPHERE
OF DONOR EXPLOSIVE IN PLACE



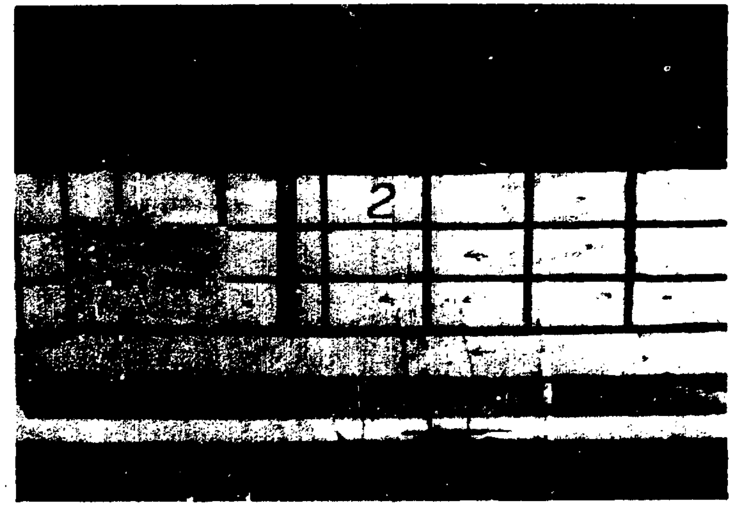
BAY STRUCTURE AFTER DETONATION OF DONOR

FIGURE 11

SCALED BAY TESTS ROUND 2 (3,000 LBS. HE EQUIVALENT)
CENTER WALL, ACCEPTOR SIDE

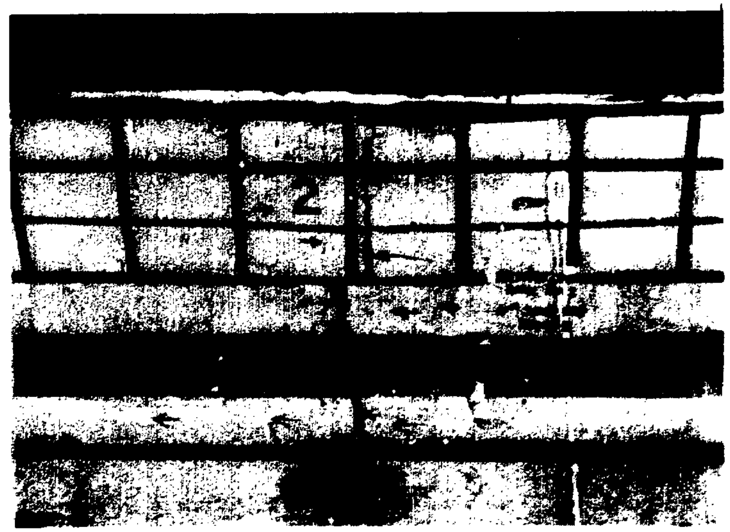


1/3 SCALE BAY Z = 0.68 W = 112.5 LBS.



1/8 SCALE BAY Z = 0.69 W = 60 LBS.

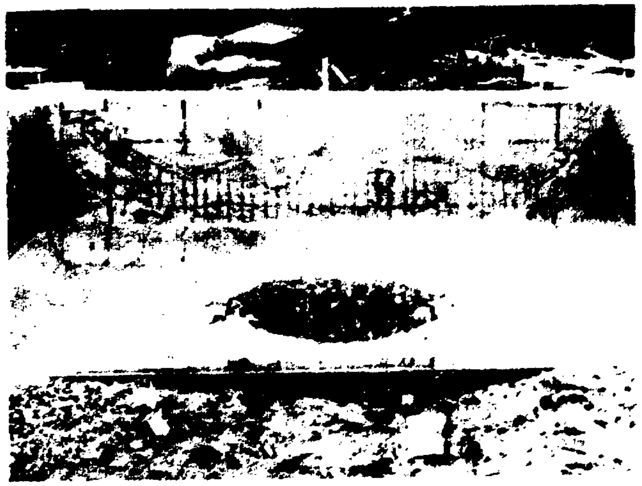
1/5 SCALE BAY Z = 0.688 W = 24 LBS.



1/10 SCALE BAY Z = 0.675 W = 3.24 LBS.

FIGURE 12

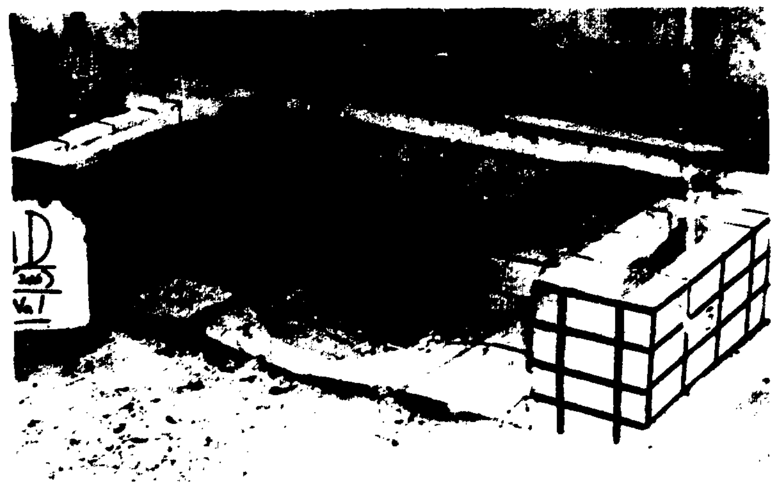
SCALED BAY TESTS ROUND 2 (3,000 LBS. HE EQUIVALENT)
DONOR SIDE



1/3 SCALE BAY
Z = 0.68, W = 112.5 LBS.

1/8 SCALE BAY
Z = 0.69. W = 6.0 LBS.

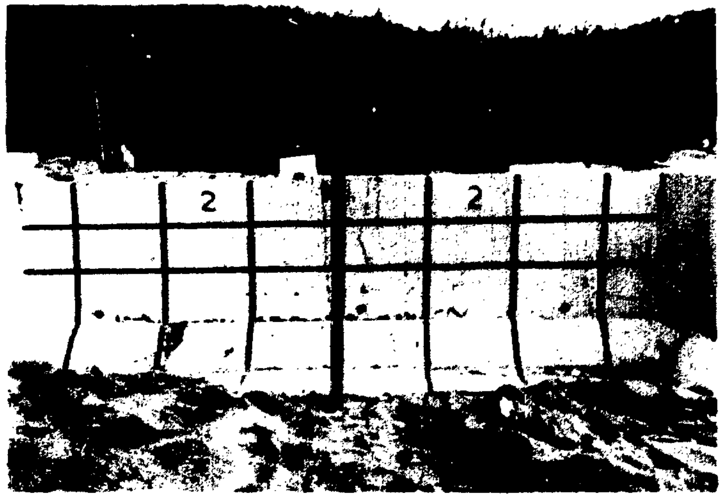
1/5 SCALE BAY
Z = 0.688. W = 24 LBS.



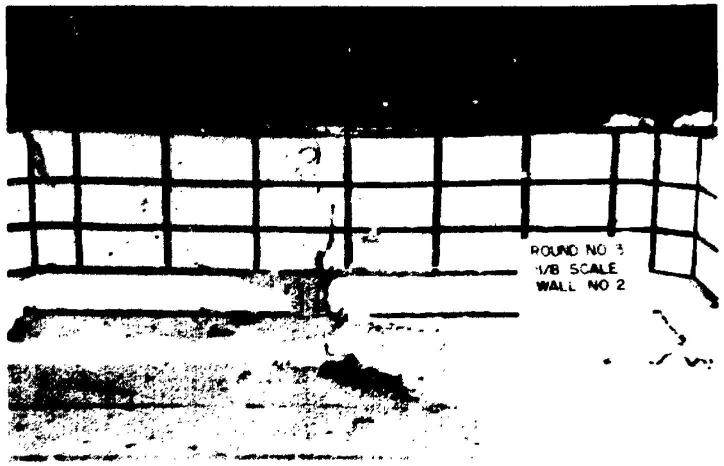
1/10 SCALE BAY
Z = 0.675. W = 3.24 LBS.

FIGURE 13

SCALED BAY TESTS ROUND 3 (5,000 LBS. HE EQUIVALENT)
CENTER WALL, ACCEPTOR SIDE

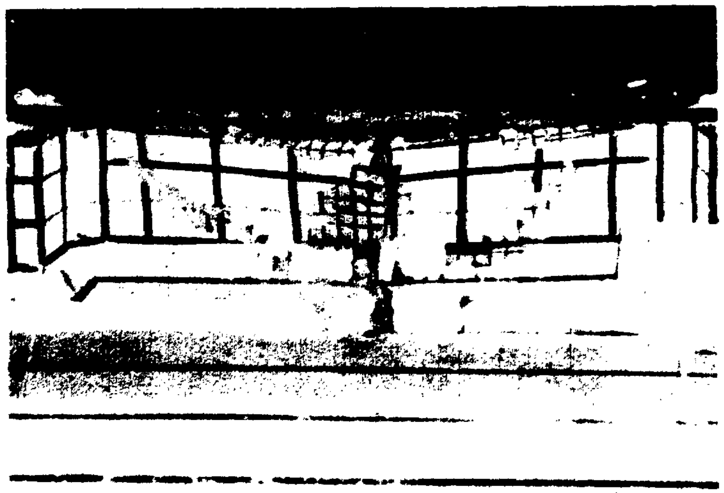


1/3 SCALE BAY Z = 0.53 W = 112.5 LBS.



1/8 SCALE BAY Z = 0.58 W = 10.0 LBS.

1/5 SCALE BAY Z = 0.58 W = 40 LBS.



1/10 SCALE BAY Z = 0.62 W = 4.24 LBS.

FIGURE 14

SCALED BAY TESTS ROUND 3 (5,000 LBS. HE EQUIVALENT)
DONOR SIDE

1/3 SCALE BAY
Z = 0.53, W = 112.5 LBS.

1/8 SCALE BAY
Z = 0.58, W = 10.0 LBS.

1/5 SCALE BAY
Z = 0.58, W = 40 LBS.

1/10 SCALE BAY
Z = 0.62, W = 4.24 LBS.

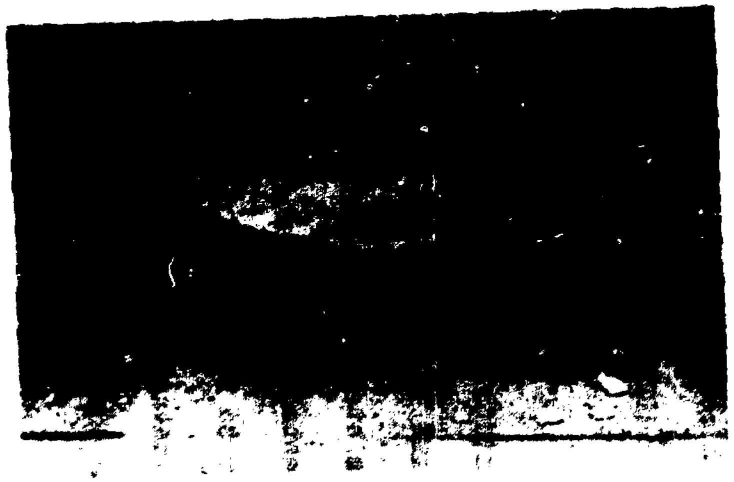
FIGURE 15

SCALED BAYS TESTED TO DESTRUCTION

ACCEPTOR SIDE

DONOR SIDE

1/8 SCALE BAY. 4TH SHOT TESTED WITH 15 LBS. OF HE (EQUIVALENT TO 7,500 LBS. OF EXPLOSIVE). FRAGMENT VELOCITY ABOUT 100 FPS.



ACCEPTOR SIDE

DONOR SIDE

1/10 SCALE BAY. SINGLE SHOT. TESTED WITH 10 LBS. OF HE. (EQUIVALENT TO 10,000 LBS. OF EXPLOSIVE). FRAGMENT VELOCITY ABOUT 150 FPS

FIGURE 16

Application of Results of Supporting Studies Program

The information developed in this supporting studies program is being used in a most practical manner.

Design charts are being developed based on slab and bay test results which will make it possible for an Engineer to tailor a storage or manufacturing facility to the exact requirements with reasonable assurance of the results in an explosive incident. These design charts will permit the design Engineer take into account such factors as weight of explosives to be contained, size of structure permissible, storage configuration required, the degree of protection to acceptors desired, amount of real estate available etc. He will be able to design a structure of maximum capacity at lowest cost.

Although these design charts are not yet available, some of the information used to develop them is now being applied by the Corps of Engineers in cooperation with Ammann & Whitney to design two new ammunition renovation facilities to be built by the Department of the Army.

Future Work:

In addition to the work being done on high capacity reinforced concrete structures and their improvement work is in progress on the use of such materials as steel for the structures required. This work will include a series of tests of scaled model slab and cubicles of prototypes structures which appear to have high blast resistant capacities. Such structures would have the advantage of being less massive with greater strength although costs may be somewhat higher.

POWERS, HQ USAF: One question I have is, did the tests indicate that a double wall with just a space between was better than the one filled with sand?

WACHTELL: In the slab test that we ran we tested a double wall with an air space and we obtained much more damage than we did with a double wall and sand in between.

POWERS: You obtained more damage?

WACHTELL: More damage with just an air space. There was apparently less attenuation of the shock thru air than there is thru sand.

POWERS: How about for fragmentation purposes?

WACHTELL: For fragmentation purposes, there would be more spalling where there is nothing behind the wall than with sand behind the wall.

POWERS: How would it affect the second wall?

WACHTELL: These spall velocities are so low that they don't have much affect on the second wall. In the Z values that we've been working with here, the spall velocities are quite low.

POWERS: I notice that in the reinforcing design of this sample structure that you had there, you had the shear reinforcing in the bottom half of the wall in one direction and the top half of the wall in another direction?

WACHTELL: That's right. This is put into the wall at the points of maximum stress. Otherwise there is no point of putting a lot of extra steel into a wall you don't need. By the way, there is a model of this prototype test bay in the back behind the projection room with a small sample of the actual reinforcing design that's in the wall. If anyone is interested in looking at it, you can see what the reinforcing patterns actually look like.

POWERS: What is the basic purpose of the design? Is it to prevent propagation to adjacent weapons or is it to protect people on the other side of the wall?

WACHTELL: The basic objective is either to prevent propagation or to protect people or to protect equipment and you can, from the information we will have at the time our design manual is written, design to any level you wish. Where it's just a storage problem and you want to prevent propagation then your capacity becomes greater or your design requirement becomes lower. Where you have to protect

personnel, then you have a design to protect personnel; in other words, you've got to prevent actual spalling of your wall and also design to prevent leakage pressures from becoming too high so that they destroy the personnel regardless of whether the wall is destroyed or not. You have to design to the particular requirement but you can on the basis of the work that we've done. We feel you will be able to design to any requirement that you set up.

POWERS: From the design that you used on these samples, I assume that you're going to use a frangible roof. If you used a solid tied-down roof then you wouldn't reinforce it the way you did in the sample. Is that correct?

WACHTELL: If we use a tied down roof, what it does is decrease the capacity of the bay in effect because then the output of the explosive is more effective and if you'll recall in the initial part of my talk I mentioned that we measure the output of the explosive in terms of its environment. If we have a 5-sided bay rather than a 4-sided structure, then the output of the explosive in effect is greater. You have to design for that also and this also will be included in our design manual. This is part of our design procedures.

POWERS: Would you say that from the results of this test that you made on that sample that the walls were too strong?

WACHTELL: I would say that we designed for 2,000 pounds for no damage to the outer wall.

POWERS: What is the purpose of your design then?

WACHTELL: The purpose of the design was to design the outer walls so that they would withstand 2,000 pounds of explosive. At the time that the initial design was made we still didn't have all the information that we needed in terms of the difference between the dynamic and static response of concrete and if you recall Mr. Dobbs' talk, he mentioned that the high pressure short duration type of load puts much less stress on the wall than a long duration type of load and we found on these tests that the walls actually were initially overdesigned and the capacity was much greater than we had originally anticipated.

COURTRIGHT, LASL: What is the increased cost of using fibre in the concrete?

ROBERTS: At the present time nylon amounts to 60¢ to $1.00 per pound, wire fibre amounts to around 40¢. We do have hopes of reducing the cost of wire fibres to possibly in the neighborhood of 12¢ a pound. Per yard of concrete that means about 25 pounds of nylon. In poundage your steel wire is about seven times as heavy as nylon so you're running into high priced concrete per yard. It would have to be a special purpose concrete.

TWEED, MARTIN: I believe Mr. Rindner stated that Comp. B would be initiated at 400 ft. per sec. with fragments whereas plastic bonded explosive was much less.

RINDNER: Yes.

TWEED: Which plastic bonded explosive?

RINDNER: PBX 9404.

PERKINS: I would like to stress that all of this work is covered by reports when the work is sufficiently complete that reports can be issued. Those reports are being made available thru the Defense Documentation Center and other normal distribution channels to any of you who are interested in specific phases of the work. We will be glad to help you get any further information on this that you will need. Also we will discuss it during the rest of the Seminar with any of you who have any questions.

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THE BERYLLIUM OXIDES OF PROPELLANT FUME:
Our Knowledge of Their Physico-Chemical and Toxicological Properties

by

Dr. Kenneth D. Johnson
Atlantic Research Corp.

INTRODUCTION

The use of beryllium as a fuel in solid rocket propellants is rapidly progressing from the research and development stage to possible application in operational missile systems. When this does occur, the safety and toxicity characteristics of these propellants and their combustion products will no longer be the exclusive concern of a limited group of people in a few propellant development firms. The transportation, storage, checkout and launch of beryllium-containing motors will involve organizations and personnel that to date have had little or no direct experience with this toxic metal, yet they must perform these tasks with full regard for the safety of both the public and the operating crews.

Basic standards will continue to be established at the national level. Supervision at the project level will have to translate these criteria into practical, day-to-day operating procedures. To do so, without imposing needless burdens or risks upon his men, his neighbors, or his budget, the project officer with this responsibility will need a clear understanding of the physiological and physico-chemical factors upon which those standards were based. Many in this audience may soon be facing such responsibility.

New data on both the physico-chemical and toxicological properties of beryllium oxide have recently become available. Drawing on these data, the National Academy of Sciences, through its Committee on Toxicology and its Advisory Center on Toxicology has recently issued new air quality criteria for beryllium and its compounds.[1] They have made the physico-chemical properties of the beryllium particles in the aerosol a determining

factor in the standards to apply in any given case. These new data and revised standards lead to a significant modification of some of the concepts and procedures that we accepted a year or two ago in formulating our hazards control programs.

The air quality criteria established by the National Research Council place differing standards upon varying forms of beryllium oxide according to their similarity, in terms of solubility characteristics, to certain forms of industrial beryllium oxides that differ in their thermal history. This represents the first time official cognizance has been taken of the long-documented relationship between the chemical and physical nature of beryllium-containing aerosols and the quantitative and qualitative differences in the hazards resulting from exposure thereto. These standards, clearly stated by the issuing body to be of interim nature only, until the results of further research become available, are:

1. "For continuous exposure to all forms of beryllium arising from industrial sources, the current level of 0.01 μg Be/m^3 averaged over a 30-day period should continue to be used.

2. "For intermittent exposure to soluble compounds of beryllium arising from rocket motor firing, a maximum atmospheric exposure of 75 μg-min Be/m^3 may be tolerated within the limits of 10-60 minutes accumulated during any two consecutive weeks.

3. "For intermittent exposure to beryllium oxide arising from rocket motor firing and which has the physical and chemical characteristics of "low-fired" beryllium oxide comparable to a product calcined at temperatures around 400°C, a maximum exposure of 75 μg-min Be/m^3 may be tolerated within the limits of 10-60 minutes accumulated during any two consecutive weeks.

4. "For intermittent exposure to beryllium oxide arising from rocket motor firing and which has the physical and chemical characteristics of "high-fired" beryllium oxide comparable to a product calcined at temperatures in excess of 1600°C, a maximum exposure of 1500 μg-min Be/m^3 may be tolerated within the limits of 10-60 minutes during any two consecutive weeks.

5. "In applying the above criteria for intermittent exposure to a rocket motor firing, it will be necessary to consider simultaneously the concentration of soluble beryllium compounds, the "low-fired" beryllium oxide and the "high-fired" beryllium oxide and adjust the limits accordingly. For example, if the rocket effluent is composed of acid-soluble beryllium (36% HCl diluted 1:1) in amounts greater than 1% but less than 5%, the "high-fired" limit of 1500 μg-min Be/m^3 should be reduced by a factor of 2; if greater then 5%, the limit for "low-fired" beryllium should be used."

You will note that although the recommended procedure for the application of these standards to rocket exhaust aerosols is based upon but a single analytical criterion -- solubility in six normal hydrochloric acid, under unspecified conditions of time and temperature, the rules themselves refer to "the physical and chemical characteristics .. of a product calcined at a temperature..."of 400° or 1600° Centigrade, as the case may be.

This language raises at least three very fundamental questions: (1) What are the chemical and physical properties of these oxides, and how do they differ? (2) Why were these particular forms of the oxide selected as reference compounds? and (3) Just how similar are propellant combustion product oxides to them?

TOXICOLOGICAL EXPERIENCE WITH BERYLLIUM OXIDES

To place these questions in the proper historical sequence, let us first consider the second one. Industrial experience[2] had clearly demonstrated that the oxide, calcined at high temperatures for use in ceramics, produced far less illness among the populations exposed to it than did a particular oxide that was employed in the formulation of phosphors for the fluorescent lamp and neon sign industries. This latter form was prepared at a 400°C calcining temperature. Qualitative and quantitative differences in toxicological properties of the high- and low-fired grades

of the oxide were first confirmed by inhalation studies conducted by Hall, Stokinger, et al[3], at the University of Rochester. The most recent and extensive data come from the work of Spencer[4], at the Dow Chemical Company, who has been testing an extensive series of carefully characterized oxides by intratracheal injection in small laboratory animals.

These studies all confirm the existence of qualitative and quantitative differences in the tissue responses to the various types of beryllium oxide. Among the various hypotheses offered to explain the differences were the partical size (in particular the specific surface), the "age" of the particles at the time of inhalation, and the thermal history per se. Spencer's work would seem to implicate some factor intrinsically associated with the thermal history. He has demonstrated an orderly and progressive increase in the speed and severity of the tissue reaction to the oxide as the calcination temperature is decreased. Microscopic studies of the lung tissues from the experimental animals strongly suggest that this is not merely the result of an increasing incidence of "reactive" particles in a larger population of inert material. Rather, the tissue reactions appear to be rather uniform for most of the particles of a given preparation and to be characteristic of the temperature at which that sample was calcined. The amount and speed of translocation of beryllium from the lungs to other body organs was also found by Spencer to show a similar correlation with the thermal history of the oxide.

Intriguing though these data may be, there is still much that we do not know or understand about the factors determining oxide toxicity. Our industrial record is sketchy and incomplete. In the days before stringent industrial hygiene controls were adopted by the industry, records of the

levels and durations of exposure, the identity and health of the exposed populations, and of the physico-chemical characteristics of the aerosol particles, were meager or nonexistent. It is only during the last few years that any serious effort has been made in routine monitoring programs to as much as discriminate between "respirable" and "non-respirable" particulates in the total air samples.

The animal data are also subject to question. The validity of animal responses as a measure of the ability of the test material to produce chronic beryllium disease in human subjects is still an unsettled question. Acute beryllium pneumonitis is clearly a single disease, whether it develops in humans or animals. Beryllium compounds that have caused the acute disease in humans will predictably produce a corresponding response in suitably exposed laboratory animals. This is not true in the case of the chronic disease.

Although "berylliosis" and "beryllium granulomatosis" have been widely used designations for chronic beryllium disease, these are misnomers for what is basically a systemic disease, with recognizable beryllium injury appearing in many tissues and organs. The granulomatous nodules found in the lungs of sufferers from chronic beryllium disease are certainly a prominent histological feature, but they do not account for the respiratory embarassment responsible for much of the disability associated with this disease. The characteristic lesion is a biochemical one - a defect in the mechanism for the transport of oxygen across the membranes separating the air spaces of the lung from the blood in the pulmonary capillaries.

The reason for this transport defect is not apparent on histological examination. Its presence in experimentally-exposed animals has never been demonstrated. The hypothesis that all beryllium compounds that will produce granulomas in animals will also produce granulomas AND oxygen transport defects in humans is attractive, but it still remains just that, an hypothesis. Until test methods and animal species have been found by which a correspondence of both the structural and functional lesions of both the animal and human subjects may be demonstrated, we ought not extrapolate negative data from animal tests to a prediction of an absence of human risk to chronic beryllium disease.

Direct human experience is convincing, however, and the animal data certainly does nothing to lessen our confidence in the conclusion we draw from that experience. The nature and degree of risks to humans exposed to beryllium oxides of the types described in our new standards are grossly different, and the industrial hygiene standards imposed for the control of these risks may justifiably differ for the "high-fired" and "low-fired" oxides.

OXIDE PROPERTIES: THEIR DEPENDENCE ON THERMAL HISTORY

This brings us back to the first of the questions we posed in our introductory remarks - just what are the physical and chemical differences between the "high-fired" and "low-fired" oxides of beryllium? Studies on this problem have been stimulated by two quite different considerations - one is the toxicity question, and the other is the matter of utilization of beryllium oxide as a highly refractory ceramic material.

Beryllium oxide can be prepared by calcining any of a number of compounds of beryllium. The sulfate, basic acetate, nitrate and hydroxide have all been used in commercial processes. For the sake of simplicity, let us confine this discussion to the changes that occur as precipitated beryllium hydroxide is heated. The first thing that happens is that chemically bound water is driven off, with the formation of an oxide. The rate of water loss, as shown in Figure 1, from the report of Livey and Williams[5], exhibits a sharp inflection after a little over eighty percent of the water has been driven off.

The molecular species persisting above the knee of this waterloss curve is generally interpreted to be one or more complex hydrated oxides. Whatever the molecular structure of this "hydrated oxide", it does not lose all of its water until the temperature has been increased to about 500°C.

On further heating, crystallite size increases rapidly, and specific surface correspondingly decreases. Although there are no obvious discontinuities in the curves of these properties when plotted against calcining temperatures, the behavior of the oxides as ceramics clearly indicate that there are at least two more critical temperatures at which some undefined, but clearly recognizable changes occur in the physical properties of the oxide.

To prepare ceramics from beryllium oxide, the material may be cold-pressed into shapes, with or without the aid of organic binders. After drying these are then sintered by heating at temperatures of 1600°C or higher. If oxide powders prepared at temperatures of less than 900°C are used, excessive shrinkage, warping, and cracking occur during sintering. If oxides prepared by calcining at temperatures much over 1250°C are used,

sintering does not occur at 1600° and strong, dense ceramic bodies cannot be formed. Oxides prepared at intermediate temperatures - above 900° but not over 1250°, are "active" enough to sinter into strong ceramic shapes, but are stable enough to prevent excessive shrinkage.

It is obvious that some rather fundamental changes are occuring in the nature of the oxide as it passes through these critical heat zones. We may speculate that the high physiological activity of the "400°" oxide is associated with either the hydrated oxide or with some molecular species that is largely destroyed at the 900° temperature, and that the "high-fired" oxide, of minimal toxicity, does not constitute the "sole survivor" form until calcining temperatures are well past 1250°. Whether the intermediate physiological and sintering activities of the oxides prepared at intermediate temperatures are indicative of still another form, or whether they merely represent a blend of the high- and low-fired forms is not established with certainty, but both lines of evidence suggest that the former is the case.

It is clear that the physical and chemical changes that take place during the calcining process are time- and temperature-dependent. These two factors have not been clearly separated in the preparation of oxide samples for the toxicological studies. It is probable that the oxide samples prepared by Spencer were held at temperature long enough for chemical equilibrium to have been reached. It must be recognized, however, that the crystallite growth achieved in any sample is rate- and time-limited, and does not represent a thermodynamic equilibrium point.

Brush Beryllium Company [6, 7] has prepared and characterized some carefully graded series of oxides that were submitted to Dr. Spencer for

use in his animal program. The series prepared by the calcining of β-beryllium hydroxide is presented in Figures 2 through 6.

The "Phase A" found by x-ray diffraction in the 700° sample is tentatively identified by Brush as a hydrated oxide. This is consistent with the results reported by Livey and Williams for the ceramic oxides, and its disappearance from the 900° sample further parallels their results.

The "Phase C" reported for samples prepared at temperatures of 1100°C and over is attributed to impurities in the oxide. Apparently there is nothing in the x-ray diffraction pattern of the "BeO" phase present in these samples that correlates in any way with the behavior on sintering of oxide powders prepared over this intermediate temperature range.

Because of the extensive agglomeration of the primary particles in these samples, microscopic sizing, sieving, or similar techniques of particle size distribution measurement are of limited value. The crystallite size measurement, by line-broadening of x-ray diffraction patterns, rapidly loses precision above 2000° A. The specific surface measurements by nitrogen absorption are probably the best measure of average primary particle size. These are plotted versus calcining temperature in Figure No. 7. For a basis of comparison the specific surface of a sample of BeO consisting of uniform hexogonal cylinders with length and diagonal diameters both one micron, would be 2.19 m^2/g. The predominance of agglomerates in these samples is shown by the fact that the 1500° sample, with a specific surfaced 2.12 m^2/g, was found by sieve analysis to have a mass median diameter of forty microns.

The physical properties of "normal" crystalline beryllium oxide are shown in Table 1.

TABLE 1

Properties of Crystalline Beryllium Oxide

Crystal System	Hexagonal
Lattice Dimensions (21°C)	
a	2.6979°A
c	4.3772°A
Density	3.025 g/cm^3
Index of Refraction	
ω	1.719
ε	1.733
Melting Point	2570°C
Boiling Point	3900°C

It now appears [8, 9, 10] that at the melting point, the beryllium oxide exists in a cubic phase; the transition occurs at about 2050°C, with a marked volume change. The x-ray diffraction pattern, made at a temperature above the transition point, indicates a 4.76°A lattice spacing. On cooling through the 2050°C, the oxide rapidly reverts to the hexagonal phase.

Recent observations made at Aeroneutronics [11] suggest that under some conditions of motor firing, the beryllium oxide in rocket exhausts may cool through the transition temperature so rapidly that the cubic phase may persist, as a metastable form, in the material collected from the firing. This raises the possibility of preparing beryllium oxide

samples rich enough in the cubic phase to permit characterization of its physical, chemical, and physiological properties. To date, this has not yet been done.

COMPARISON OF ROCKET-EXHAUST AND INDUSTRIAL OXIDES

We come now to the last of the questions raised by the National Research Council's recommended standards - just how closely do the rocket exhaust oxides resemble the high-fired oxide prepared by furnace processes?

The temperatures in a rocket motor chamber are so high, in comparison with the 1300° to 1600°C calcining temperature required for the production of high-fired oxide that, as first thought, there would seem to be little reason to raise any question as to the correspondence between the two. However, in the highly dispersed exhaust fume, there is little if any opportunity for the interactions between primary particles that characterize much of the change in properties of the industrial oxides as they undergo calcining in a bulk process.

A direct comparison of the oxides from the two sources, by strictly comparable measurement techniques, would seem to provide a direct answer to our question. One handicap to this approach is the lack of acequate rocket exhaust samples. To the best of my knowledge, no bulk sample of beryllium oxide, from a normal, open-air firing of a large motor, has ever been collected.

Most of the comparisons have been performed on oxide samples collected from firings in small chambers. Under these conditions, the rates of cooling, the exposure of the hot oxide to water vapor, and the opportunities for agglomerate formation are all quite different from that which would be

the case for the processes operative in a normal firing. Another factor present in many of these firings has been the opportunity for post-firing changes in the oxide as a result of attack by hydrochloric acid, in both a gaseous and condensed form. The contamination of the beryllium oxide by metallic compounds from igniter components, acid attack on motor and test chamber components, etc., cannot be ignored.

The comparisons that I will present today will be based upon oxides, subject to all the defects enumerated above, that were collected in a closed chamber program at Atlantic Research[12] in a project sponsored by the Air Force Rocket Propulsion Laboratory. The data came from analyses performed by Atlantic Research, by Aeroneutronics, and by the Dow Chemical Company.

The Dow work represents the best series of measurements in which the rocket-exhaust and industrial oxides were measured by identical techniques. Tables 2, 3, and 4 tabulate the values obtained by Dow for their "reference" industrial oxides and selected rocket exhaust products.

The particle size values for the exhaust oxides in Table 2 were derived from analysis of electron micrographs. There is good reason to believe that, in the preparation of the specimen mounts, the larger particles were discriminated against. The specific surface measurement is believed to be a more valid index of average particle size ($\overline{D_s}$) in the bulk sample.

The physical appearance of these exhaust particles is shown in Figures 8, 9, and 10. Note the similarity to the crystalline particles seen in the high-fired oxide samples, particularly those fired at 1100° and 1300°C. Figure 11 is an enlargement of a portion of the field shown in Figure 4; the faces of the hexagonal plates are clearly distinguishable.

The predominance of monocrystalline particles in the exhaust fumes from beryllium propellants came as a distinct surprise to those of us familiar with the aluminum oxide particles found in the discharge from rocket motors. A typical preparation is shown in Figure 12. This is just what one would expect to find as a result of the thermodynamically predicted sequence of events: (1) vaporization of the metal, (2) vapor phase oxidation, (3) condensation of the oxide vapors in the motor chamber to form droplets of molten oxide, (4) ejection of the liquid droplets through the nozzle, and (5) "freezing" of the droplets into beads of polycrystalline oxide.

It is obvious from the appearance of the beryllium oxide particles that, at some point in the process of their formation, the mechanisms operative in the case of the aluminum oxide have been replaced by different and unidentified ones. It is not easy to formulate a hypothetical series of events, consistent with known properties of beryllium oxide, that could reasonably be expected to yield monocrystalline fume of the type we find.

My friends skilled in internal ballistics assure me that the C* values measured for beryllium propellants unequivocally establish that the beryllium oxide passes through the nozzle as a condensed phase. The temperatures within the motor chamber are many hundreds of degrees above the normal melting point of beryllium oxide. The formation and persistance of crystalline beryllium oxide in the motor chamber could only occur if, at these temperatures and pressures, some new and previously unknown phase of beryllium oxide, with a melting point far above that observed at atmospheric pressure, should be stable under such conditions. No other evidence suggests that such a BeO phase exists.

It is difficult to visualize fluid mobilities that would permit the orientation of the liquid BeO into the well-formed, complete crystals common in the exhaust products, and to the substantially complete exclusion of spherical, polycrystalline beads, in the millisecond time intervals during which the particles cool through the solidification temperature range. Until one can rationalize the formation of monocrystals of "normal" hexagonal beryllium oxide with the time, temperature, and pressure history of the exhaust particulates, the identity between the two forms of beryllium oxide remains subject to question.

I have earlier referred to the detection of a cubic phase in these exhaust products, and its tentative identification with the form of beryllium oxide thermodynamically stable above 2050°C. This work was done at Aeroneutronics, who reported this phase present in some, but not all, of the exhaust products collected from Atlantic Research's Stansel tank firings, but in all of four samples collected from open-air firings at Edwards Air Force Base. If, in fact, this does represent material "frozen" in a metastable form by rapid cooling through the transition temperature, it is to be expected that this cubic phase may become increasingly dominant under conditions favoring rapid dilution and cooling of the plume. Free flight would certainly be such a condition. No oxide samples have ever been collected under free-flight conditions, or from wind tunnel tests in which such free-flight velocities were simulated.

The nature of the oxide produced under conditions of burning at atmospheric pressure is another unknown. Combustion efficiencies are generally very low, but some oxide fume is generated. Small lots of propellant, containing a high ratio of aluminum to beryllium, will burn hot enough to result in conversion of all the beryllium to the oxide.

Straight beryllium propellants, when burned at atmospheric pressure, yield a binder phase-oxidizer flame with relatively little combustion of the metal. This has proved true even in the case of large motors in which "normal" combustion patterns had been established before case failure. When the pressure dropped back to ambient at case failure, the remaining propellant burned out leaving a major portion of the contained metal as a residue of metallic particulates only thinly coated with oxide.

To summarize the answer to our original question: There are striking similarities between high-fired oxide and the hexagonal-phase oxide present as a major phase in the exhaust products from normal static firings. Our inability to rationalize the existence of such a material in the exhaust products, and the probable presence of a cubic phase in many exhaust products, limit the extent to which we may extrapolate toxicological data on the high-fired oxide to the rocket exhaust material. Direct comparison of tissue response data appears more convincing.

TOXICOLOGICAL DATA

Experimental studies* of the toxicological properties of rocket-exhaust oxides may be divided into two groups: (1) those in which animals were exposed directly to the freshly generated, total combustion products of the propellant, and (2) those in which the test material was solids collected from previous firings.

Atlantic Research Corporation[13, 14, 15] conducted an extensive series of tests in which dogs and/or rabbits were exposed to the total fumes generated by the combustion of test propellant formulations. Exposure periods

*All experiments reported herein were conducted according to the "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

were brief -- usually twenty to thirty minutes. Fume concentrations were high, the total dosage typically being in the 200,000 to 2,000,000 microgram minutes per cubic meter. In each series, control exposures were performed with propellants of equivalent stoichiometry, but with aluminum rather than beryllium or the metallic fuel.

There were three series of such experiments: (1) exposure to combustion fumes of propellants oxided with ammonium perchlorate, (2) exposure to combustion fumes from propellants releasing no acid gases, and (3) exposure to the combustion products of propellants formulated to yield high concentrations of fluoride in the reaction products. The acute responses of the animals to these exposures are summarized in Tables 5 to 7.

With the exception of the animals exposed to beryllium fluoride-containing fumes, no acute responses were found in any of these groups that could be definitely ascribed to beryllium injury, or that differed significantly from the responses observed in the control groups exposed to the aluminum analogs.

The findings of late-developing beryllium granulomas[16] in two of six dogs exposed to the halogen-free fumes of BeO and beryllium metal, were unanticipated. At no time had these animals ever exhibited any evidence of beryllium injury, either at Atlantic Research's laboratories or after their transfer to the Aerospace Medical Research Laboratories at Wright-Patterson Air Force Base for long-term holding. The granulomas were detected at micropsy, and their identity confirmed by the demonstration by a laser-spectrographic technique, of beryllium in the granulomas and the absence of beryllium in the adjacent, normal appearing tissue.

The low combustion efficiency experienced in the motor firing by which the test fume was generated raises serious doubt as to the nature of the beryllium oxide present in the fume, and the undoubted presence of major amounts of metallic beryllium makes uncertain the implication of the oxide, in any form.

The acute responses to the beryllium fluoride fume present no mystery. Whether the delayed development of granulomas in the dogs, (but not the rabbits) involved in this exposure is a consequence of the BeO, per se, the BeF_2, or of a synergistic effect of the combination cannot be decided upon the basis of the available data. I wish to emphasize that there was no evidence of clinical illness in these dogs at the time of sacrifice. No pulmonary function studies were performed.

The early development of a practical propellant yielding combustion product similar to those to which these animals were exposed now seems to be a probability. The implications of our pilot studies strongly suggest that both the physico-chemical and the toxicological properties of the beryllium oxide in this fume, and any possible synergism between the oxide and fluoride, receive prompt attention.

As subcontractors to Bionetics Research Laboratories, we recently completed the exposure of a group of dogs and monkeys* to an aerosol of exhaust oxides (Sample 24) collected in our Stansel tank program. Three half-hour exposures, at one-month intervals, were given these animals to an aerosol with nominal concentration of 4 mg of Be (11.1 mg BeO) per cubic meter. These animals will be followed over a five year period. No acute or delayed responses have yet been observed.

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*Sponsored by the Airmedical Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base under Contract AF 33(615)2999.

Dr. Spencer, at Dow Chemical Co., has been testing both his furnace-prepared oxides that were described in previous slides, and selected samples of rocket exhaust beryllium oxide, by intratracheal injection in small laboratory animals. His early tests used the total collected exhaust products, and with the relatively massive doses administered to the animals, he observed severe acute irritation from the soluble constituents present as minor impurities in most of the samples.

More definitive tests, with the insoluble portions only of these exhaust products, indicate a close similarity in tissue responses to those experienced with the high-fired oxide. These include: minimal foreign-body response, the extracellular, rather than intracellular, location of most oxide particles in the lung tissue sections, and the very slight degree of translocation of beryllium from the lungs to other tissues.

These direct observations are, in my mind, more convincing than the less-than-perfect correspondence of physico-chemical properties between high-fired oxide and the haxagonal oxide generated by normal motor firings. However, the two lines of evidence reinforce each other. Their sum suggests that the disease-producing potential of this form of oxide in the normal individual is minimal. The innocuousness of it to the "hyper-susceptible individual" if such exists, is less clearly evident.

The question of the cubic phase oxide, and the definition of the conditions under which its formation is probable, remains for future work to resolve. This problem is closely related to the one of characterization of the aerosols generated by open combustion of beryllium-containing propellants. There are reasons to suspect that the cubic phase oxide will be found in large quantities in the fume from such an event.

Of all the incidents we might postulate that would result in a massive over-exposure of a neighborhood population to a beryllium combustion product fume, the ignition of a non-propulsive motor in storage or transport by an accidental fire, would seem to be least unlikely. This consideration justifies a prompt and vigorous effort to characterize the nature and degree of risk resulting therefrom.

CONCLUSIONS

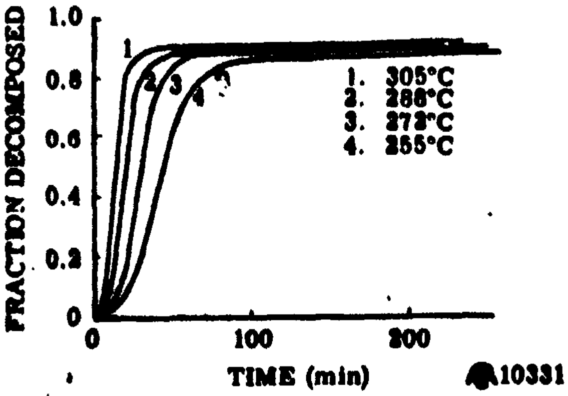
In summary, I believe the data now available entitles us to draw several reasonable conclusions:

1. The minimal tissue reactivity of high-fired beryllium oxide does justify the relaxation of air quality standards when only this form of beryllium is involved.
2. The close similarity in many physico-chemical properties between the "normal" hexagonal beryllium oxide propellant fume, and the "high-fired" oxide, combined with the experimentally observed inertness of this material in animal tests, strongly suggest that it is unlikely to produce illness in normal humans as a result of the exposures probable from a credible accident.
3. Not enough is known concerning the relationship between physico-chemical properties of the exhaust oxide and the parameters of motor burning to permit the application of the proposed "relaxed" standards of the National Research Council to be applied, on an a priori basis, to any specific planned event.

Until we have more precise knowledge on these points, the recommended standards of the National Research Council, as now written, place far greater restrictions upon beryllium operations than either the "0.01 micrograms per cubic meter averaged over 30 days" or the "750 microgram minutes per cubic meter in a single event" standards now generally applied to these situations.

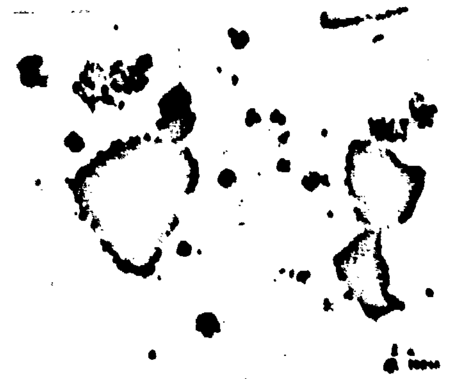
The large percentages of acid soluble beryllium metal, present in the fume from low-pressure combustion, would make any event subject to such an accident as case failure subject to the 75 microgram minutes per cubic meter standards. This standard applies to total beryllium if the acid soluble fraction is over 5 per cent. Thus, permissible total "acid soluble fraction" dosage may be limited to less than 4 microgram minutes per cubic meter, summed over a two-week period. This corresponds, for that acid-soluble fraction, to a concentration, averaged over a two-week period, of 0.0002 micrograms per cubic meter.

The NRC standards classify all propellant combustion product beryllium oxides into the classes resembling the "400°C oxide" and the "1600°C oxide". It is certain that all fume products do not fit into this simple dichotomy. Without a more extensive understanding of the nature of the products to be anticipated under both normal and abnormal combustion conditions, and better sampling and analytical technique to characterize the products liberated by the event when it does occur, we will find it difficult to predict, with assurance, that a test can be conducted in conformance with these standards, or to demonstrate, on an a posteriori basis, that we have in fact so done.



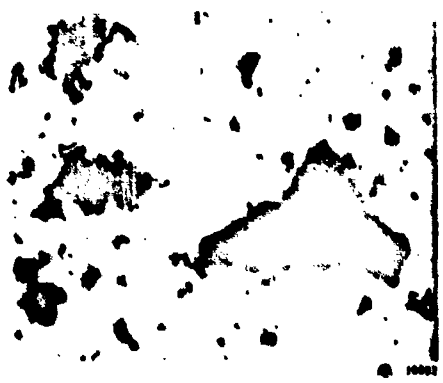
ISOTHERMAL DEHYDRATION OF $Be(OH)_2$

Fig. 1



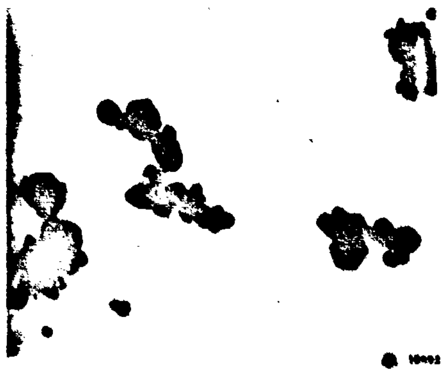
BRUSH BeO PREPARED AT 700°C
AVG CRYSTALLITE SIZE ———
SPECIFIC SURFACE 75 m^2/g
BeO - MINOR PHASE PHASE A MAJOR

Fig. 2



BRUSH BeO PREPARED AT 900°C
AVG CRYSTALLITE SIZE 220 Å
SPECIFIC SURFACE 61 m^2/g
BeO ONLY PHASE DETECTED BY X-RAY DIFFRACTION

Fig. 3



BRUSH BeO PREPARED AT 1100°C
AVG CRYSTALLITE SIZE 4000 Å
SPECIFIC SURFACE 7.7 m^2/g
BeO MAJOR PHASE "C" VERY MINOR

Fig. 4

Fig. 5

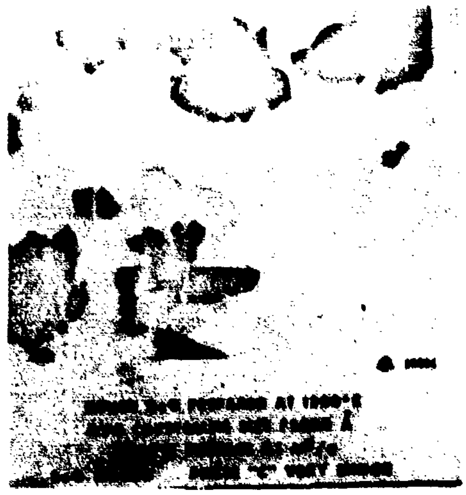


Fig. 6

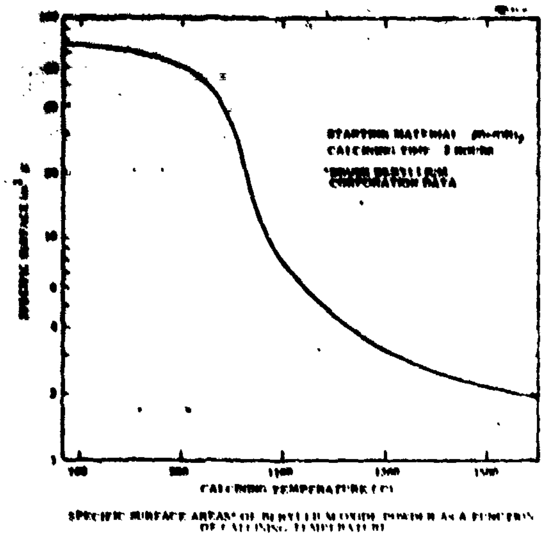


Fig. 7

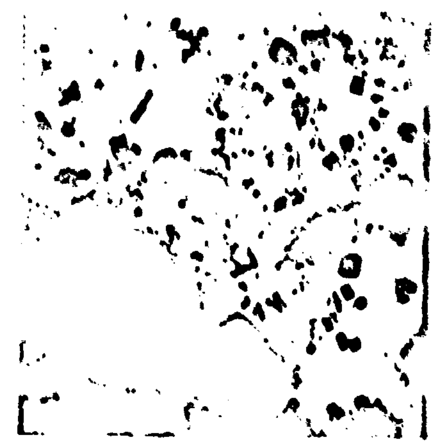


Fig. 8

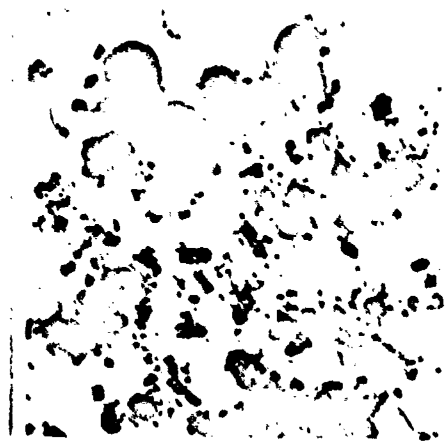
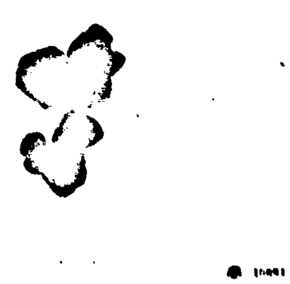


Fig. 9

Fig. 10



BRUSH BeO PREPARED AT 1100°C

Fig. 11

Fig. 12

PROPERTIES OF CRYSTALLINE BERYLLIUM OXIDE

Crystal System	Hexagonal
Lattice Dimensions (21°C)	
a	2.6979Å
c	4.3772Å
Density	3.025 g/cm^3
Index of Refraction	
ω	1.719
ϵ	1.733
Melting Point	2570°C
Boiling Point	~ 3900°C

Table 1

PARTICLE SIZE DATA

	500° Oxide	1100° Oxide	1600° Oxide	Sample Number 1	Sample Number 22	Sample Number 24
Crystallite Size Å	150	1500	1600	>5000	>5000	>500
Specific Surface m^2/g	50.8	2.2	1.3	< 2.5	0.8	0.7
$\bar{D}_V$*, μ	Agglomerates			1.96	3.00	2.90
$\bar{D}_N$*, μ	Agglomerates			0.415	278	1.29

*ARC Data

COMPARISON OF FURNACE AND ROCKET-EXHAUST OXIDES

Table 2

INDEX OF REFRACTION

	500° Oxide	1100° Oxide	1600° Oxide	Sample Number 1	Sample Number 22	Sample Number 24
10 Per Cent Below	1.680	1.703	1.706	1.700	1.706	1.706
50 Per Cent Below	1.682 1.684	1.704	1.711	1.704	1.709	1.709
90 Per Cent Below	1.686	1.706	1.720	1.708	1.712	1.712

COMPARISON OF FURNACE AND ROCKET-EXHAUST OXIDES

Table 3

DENSITY AND CRYSTALLINITY

	500° Oxide	1100° Oxide	1600° Oxide	Sample Number 1	Sample Number	Sample Number
Density g/cm^3	2.80 to 2.94	2.97 to 3.00	2.97 to 3.03	2.75 to 2.86	2.98 to 3.00	2.86 to 3.00
Crystallinity (by Optical Birefringence	<10 per cent	100 per cent	85 per cent	100 per cent	100 per cent	100 per cent

COMPARISON OF FURNACE AND ROCKET-EXHAUST OXIDES

Table 4

Fume Source	Aerosol Composition	Response				
		Eye & nose Irritation	Pulmonary Edema	Weight Loss	Acute Mortality	Long Term
Aluminum Control Propellant Motor Firing	Al_2O_3 HCl	+ to ++	+	+	1/8	None
Beryllium Test Propellant Motor Firing	BeO HCl	+ to ++	+ to ++	+	1/16	Granu lomas
Aluminum Control Propellant Atmospheric Pressure Burning	Al_2O_3 HCl	0 to +	0	0	0/8	None
Beryllium-Aluminum Test Propellant Atmospheric Pressure Burning	Al_2O_3 BeO HCl	0 to +	0	0	1/16	None

RESPONSES OF ANIMALS TO COMBUSTION FUMES OF PERCHLORATE-OXIDIZED PROPELLANTS

Table 5

Fume Source	Aerosol Composition	Response				
		Eye & Nose Irritation	Pulmonary Edema	Weight Loss	Acute Mortality	Long Term
Aluminum Control Propellant Motor Firing	Al_2O_3	0	0	?	Rabbits 0/8	None
Beryllium Test Propellant Motor Firing*	Be BeO	0	0	?	Rabbits 0/32 Dogs 0/6	Rab. None D-G**

*Motor burned at abnormally low pressure

**Dogs - Granulomas

RESPONSES OF ANIMALS TO COMBUSTION FUMES OF HALOGEN-FREE PROPELLANTS

Table 6

Fume Source	Aerosol Composition	Response				
		Eye & Nose Irritation	Pulmonary Edema	Weight Loss	Acute Mortality	Long Term
Aluminum Control Propellant Motor Firing	Al_2O_3 HF AlF_3* HCl	+	0→+	+	Rabbits 1/12	None
Beryllium Test Propellant Motor Firing	BeF_2 BeO $BeCl_2$* HCl* HF*	++++	++++	+++	Rabbits 13/24 Dogs 0/2	Rab. None Dogs Granulomas

*Minor

RESPONSES OF ANIMALS TO COMBUSTION FUMES OF FLUORINE CONTAINING PROPELLANTS

Table 7

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EVALUATION OF PROTECTIVE CLOTHING FOR USE WITH FLUORINE

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ABSTRACT

A five-phase program was conducted to evaluate chemical compatibility and permeability of various candidate protective clothing materials to gaseous and liquid fluorine. The objective of the program was to determine materials which would be compatible with both gaseous and liquid fluorine, and suitable for protective suit construction. Consequently a specification for the suit ensemble has been developed.

The test program was conducted in the following phases: 1) chemical compatibility 2) gaseous permeation 3) gaseous impingement 4) physical property deterioration 5) liquid impingement. Materials which passed the initial test (chemical compatibility) were subsequently tested for permeability, physical property deterioration, etc.

Forty-seven possible protective suit materials were selected for test. These included neoprenes, cellulose-acetate, Teflon, polyurethanes, butyls, vitons, and metalized coated laminates of various types. A total of 11 materials were compatible with gaseous fluorine. These sample materials were impinged with liquid fluorine. A total of 24 samples were liquid impinged, some being retested to verify results. The liquid tests involved impinging the samples, which were mounted on a stainless steel stand, with approximately 500 cc of liquid fluorine per sample, one inch distance from 1/16 inch jet orifice to sample, at 50 psig, from 5-8 seconds.

Colored movies and stills were made of the liquid impingement tests. Colored stills were taken before and after each chemical compatibility test.

I. INTRODUCTION

During the past year, various government agencies have shown a growing interest in fluorine as an oxidizer in liquid propulsion systems.

Boeing has been conducting laboratory and remote-site tests with both liquid fluorine (LF_2) and fluorine-oxygen (FLOX). System design parameters define requirements for remote operations of pressurization, transfer, purging, etc. However, personnel must make and break connections and perform various operations attendant to testing when system failure might present exposure conditions.

Air Force and NASA concern for personnel safety has stimulated the protective clothing manufacturers to develop suits for protection against a variety of fuels and oxidizers, yet maintaining wearability and flexibility in service. (Several suits are presently on the market, but government specifications to date have not required manufacturers to demonstrate performance in dynamic exposure environments.)

The Boeing Aerospace Group Safety Engineering organization reviewed current protective clothing practices in the chemical and aerospace industries. There is no uniformity in clothing materials being used against oxidizers such as fluorine. In fact, there is very little dynamic test data available on materials presently being used or proposed for use with fluorine.

Against this background we undertook a test program whose objective has been to evaluate those materials in use or proposed for use under dynamic conditions of exposure to gaseous and liquid fluorine. From these evaluations a determination has been made of the most suitable material and a specification developed for protective-suit construction.

II. TECHNICAL APPROACH

A. General

Forty-seven possible protective-suit materials were selected for test. These included butyls, neoprenes, cellulose acetate, Teflon, FEP,

Kel-F, polyurethanes, Armalon 97-001, Armalon 97-001A, and Armalon 97-001G. Armalon is a Du Pont trade name used to identify a Teflon laminate consisting of Teflon fabric 0.008 inch thick overcoated on one side with Teflon (FEP) 0.005 inch thick film, and is identified as 97-001. Some samples had a vacuum deposition of aluminum or gold and were further identified as "A" or "G" respectively after the 97-001. The selection of Du Pont's 97-001 material was based on North American Aviation, Rocketdyne Division test report No. 2091 on Contract AF04 (611)-5963, which indicated the 97-001G material to be exceptionally resistant to gaseous F_2, chlorine-trifluoride (CTF), and pentaborane.

The Boeing test program consisted of five phases:

1. Chemical compatibility tests on all material samples.
2. Gaseous permeation tests on materials that showed the best performance in Phase 1; in addition, test specific areas of suit construction (seams, joints, etc.).
3. Tensile strength tests on materials that survive Phase 2.
4. Gaseous fluorine impingement tests on materials that showed the best performance in Phases 1 and 2.
5. Liquid fluorine impingement tests on materials that performed best in Phases 1, 2, and 3.

B. Test Apparatus

The same facility was used for the gaseous chemical compatibility, permeation, and impingement tests. The facility consists of a source of fluorine gas for filling a set of six cells or jigs. Pyrex glass cells were used for the chemical compatibility studies and stainless steel jigs for the permeation studies. Fluorine gas was supplied from a cylinder enclosed in a steel barricade equipped with remote controls for operating valves. Using 0.25 inch diameter stainless steel tubing, fluorine gas was brought into the inlet manifold of the test apparatus, after passing through an absorption tube for hydrogen fluoride (HG) removal and a rotameter for flow rate measurement. The HF scrubber

contained an activated form of sodium fluoride. The entire test setup was assembled in a laboratory fume hood. Fluorine gas was introduced into each glass cell individually and valved, allowing it to have its own atmosphere independent of the others. A line from a vacuum pump, including a coil immersed in a liquid-nitrogen bath and soda-lime-packed tube, was attached to the outlet manifold. The cold trap prevented any organic vapors from the vacuum pump from entering the test area, while the soda-lime tube will prevent fluorine from reaching the vacuum pump. Nitrogen was dried by passing the cylinder gases through a coil immersed in dry ice before entering the test setup. The nitrogen gas was valved for purging any or all parts of the complete system. A pressure gage was located ahead of the fluorine flowmeter to read the pressure regulator on the fluorine cylinder. A vacuum gage, calibrated against a mercury manometer, was located on the inlet manifold.

III. PHASE 1 - CHEMICAL COMPATIBILITY TESTS

A. Specimens

The test samples were approximately 0.5 inch wide and 2 inches long. Prior to testing, the samples were solvent-cleaned, distilled water rinsed, wiped clean, and air dried.

B. Procedure

The samples were hung on stainless steel hooks located inside the glass cells. The system was first passivated with gaseous N_2, then evacuated. A vacuum was drawn and gaseous fluorine (GF_2) was then introduced into the cell until reaching a 1-atmosphere positive pressure. The samples were exposed to 100 percent GF_2 environment at 1-atmosphere for 2 hours. The samples were weighed on an analytical balance before and after exposure to GF_2 to determine any weight change.

C. Test Results

The Armalon 97-001, 97-001A, and 97-001G, butyl-coated nylon (parachute) cloth, Buna N coated nylon, Gentex 2 (Al_2-nylon-neoprene),

and Du Pont neoprene nylon 5009 demonstrated the best performances of the supported materials. Sawyer-Tower neoprene-nylon and Gralite failed this test. Several unsupported samples demonstrated good results, such as neoprenes (2-0262) (2-0022) (#89); butyls (62.72) (8.0255) (#80-011); polyurethane (UR 29E Black); Nordell (50-001); and Surlyn (A) and Viton A, 9-0277 and 80-060.

IV. PHASE 2 - PERMEATION TESTS

The same facility in Phase 1 was used for the permeation test, however, stainless steel jigs were fabricated and used instead of the Pyrex glass cells. The jigs were fabricated into two halves, with a mating flange at the equator. The diaphragms of test materials were placed between the mating equators and torqued tight. A continuous flow of dry nitrogen was passed through the top section. A fluorine atmosphere was produced in the lower section by flowing seven liters of GF_2 into and through the chamber during a 10-minute purge. The lower section was then sealed.

A. Specimens

Only samples that showed best performance in Phase 1 were tested. Each specimen began as a 6-inch square; it was then cut into the shape of a ping-pong paddle, with the "paddle" part the same diameter as the outside diameter of the permeation jig and its "handle" available for positioning the spedimen in the jig.

B. Procedure

Quantitative measuring of the permeation rate of GF_2 was accomplished by sweeping the outlet gas into a bubbler containing 10 milliliters of 0.1N NaOH through the outlet side of the N_2 jig section for 5 minutes. (A hose was connected to the outlet orifice of the N_2 half of the jig, and gaseous N_2 containing the permeated F_2 gas was bubbled into the 0.1N NaOH solution.) Previous tests indicated that this system will quantitatively absorb F_2 and HF from a gas stream. The pressure on the bottom on the F_2 side was built up to 1-atmosphere positive pressure; the pressure on the N_2 or top side of the jig was built up to 1-atmosphere plus 2 inches of H_2O

positive pressure during sampling. Bubbler sampling was done periodically during the test.

C. Test Results

Wilgard 89 (Neoprene) Glove Material (0.030 Inch Thick) - This material demonstrated the best results of all the materials tested. Two samples were tested up to 24 hours and no detectable permeation was found. Subsequent examination showed only that the exposed side had whitened somewhat.

Armalon 97-001 - This material demonstrated the best overall Teflon results with low permeation rates.

Armalon 97-001A and G - Although some samples demonstrated low permeation rates, some had high rates. Close examination revealed pin holes through the material. It is felt that in the process of vacuum deposition, there is some tendency to cause FEP film degradation.

Armalon 97-001 Containing Sewed-Sealed Seam - High permeation rates.

Armalon 97-001G, Sewn and Sealed - High permeation rates.

Armalon 97-001A, Sewn and Sealed - High permeation rates.

Cellulose Acetate Faceshield - Two samples (approximately 0.060 inch thick) were tested. No detectable permeation was found during the first four hours, and this time could be greatly increased since it was the following day before it was retested. Equilibrium values of about 13 micrograms/inch^2/hour were noted after 1 day. Subsequent examination revealed some attack, as evidenced by the pronounced odor of acetic acid. However, the material remained optically clear but slightly discolored.

Butyl (Du Pont T-5595 Sheet Stock) - One sample of Du Pont T-5595 Butyl burned immediately upon F_2 exposure.

D. **Theoretical Suit Permeation**

To get some insight as to the significance of the permeation relative to full-size fuel-handler's suits, calculations were made showing the projected suit leakage rates. Times of exposure and percentages of gaseous F_2 were varied. The calculations were based on the surface area of an average size man (15.5 ft.^{2}). The assumption is made that the suit is under two inches of water positive pressure from supplied air or its own environmental control system and no suit air dilution is taking place.

Example 1 (Leakage Rate = 10 ug/F_2/inch^2/hour)

1. Multiply the leakage rate times suit area to find the leakage per hour, expressed in ppm per average suit per hour.

2. In this example, the leakage per hour would be:

F_2 Concentration	ppm/average suit/hour
100%	169
10%	16.9
5%	8.45

3. In five minutes, the leakage would be:

F_2 Concentration	ppm/average suit
100%	14.1
10%	1.41
5%	0.71

Example 2 (Leakage Rate = 700 ug/inch^2/hour

1. Multiply the leakage rate times suit area to find the leakage per hour, expressed in ppm per average suit per hour.

2. In this example, the leakage per hour would be:

F_2 Concentration	ppm/average suit/hour
100%	11,739
10%	1,173.9
5%	586.95

3. In five minutes, the leakage would be:

F_2 Concentration	ppm/average suit
100%	978.2
10%	97.8
5%	48.9

The results shown above take on added meaning in light of emergency exposure levels established recently by the National Academy of Science. See Table 1.

Table 1: Emergency Exposure Levels

Free Fluorine

Concentration Level	Time of Exposure
5 ppm	5 minutes
3 ppm	15 minutes
2 ppm	30 minutes
1 ppm	1 hour
0.1 ppm	8 hours

Hydrogen Fluoride

Concentration Level	Time of Exposure
30 ppm	5 minutes
20 ppm	15 minutes
10 ppm	30 minutes
8 ppm	1 hour

V. PHASE 3 - TENSILE STRENGTH TESTS

A. Specimens

All specimens that were permeation tested were later tensile tested per Federal Specification CCC-T-191b, Method 5102.

B. Procedure

Specimens (1 inch by 6 inches) were placed symmetrically into the clamps of an Instron Tester, with long dimension parallel and the short dimension

at right angles to the direc' n of load application. The yarn running parallel to the long dimens .n of the specimen was aligned with one outside edge of the front jaw of each clamp to ensure the same yarns being gripped in both clamps. The tension was evenly distributed on the yarns between clamps. Force was applied at the specimen at 12 ± 0.5 inches per minute. After specimen rupture, the breaking force was read from the dial indicator and recorded. The jaws were faced with rubber to prevent slippage.

C. Test Results

The test results are shown in Table II.

Table II: Tensile Strength Tests

Material	Tensile Strength: As Received	After F_2 Contamination	Loss (Percent)
97-001	75 psi	63 psi	16
97-001A	68 psi	63 psi	7
97-001G	68 psi	64 psi	6
97-001 (Seam)	120 psi	112 psi	7
97-001A (Seam)	120 psi	115 psi	5
97-001G (Seam)	120 psi	114 psi	6
Butyl (T-5595)	1960 psi	1010 psi	48
Neoprene (Wilson 89)	3760 psi	2825 psi	25
Cellulose Acetate	7166 psi	5280 psi	26

VI. PHASE 4 - GASEOUS IMPINGEMENT TESTS

A. Specimens

Sample materials that demonstrated the best performance in the first three phases of testing were subjected to the gaseous impingement tests; in addition, three materials (8-0255 butyl, Nordel 50-001, and 62-72 butyl) that had only been given the chemical compatibility test were tested in this phase.

B. Procedure

A test apparatus similar to the chemical compatibility test equipment was used. The system was evacuated and the sample suspended 0.1 inch from an orifice (0.16 inch diameter). Gaseous fluorine was then flowed into the evacuated chamber until the pressure reached 1-atmosphere again (about 1 minute of flow).

C. Test Results

There was no visible reaction or change in the weight or appearance of the samples.

VII. PHASE 5 - LIQUID -FLUORINE IMPINGEMENT TESTS

A. General

Dynamic liquid-fluorine impingement tests were conducted at the Tulalip Remote Test Site in conjunction with Boeing Flight Technology personnel. The tests involved impinging 24 samples. Some samples were retested two or three times to verify results. Only sample materials that passed the gaseous chemical compatibility tests were liquid-impinged.

B. Test Apparatus

The 10-gallon liquid-fluorine transfer test apparatus was used for the impingement tests. Here liquid fluorine was made by condensing gas from cylinders in a liquid-nitrogen bath. The stand consisted of a stainless steel rack, subdivided into six individual cells. Each cell was partitioned by stainless steel baffles and copper wire screen for mounting the samples. A stainless steel manifold was located at the base of the test rack, to which six 0.25 inch diameter stainless steel lines were welded. The lines were arranged so that each sample was impinged separately. The lines were restricted at the exit end by installing an AN 818-4B nut and an AN 806-4 plug with the plug drilled to a 1/16 inch diameter orifice.

C. Samples

The test samples were approximately 6 by 6 inches and were solvent cleaned, water rinsed, and air dried prior to testing. One impingement was conducted per sample.

D. Procedure

The samples were mounted to the copper screen holder. The jet orifices and samples were protected from moisture by placing a small bag over the purging jet orifice and a small Teflon shield over each sample to protect against atmospheric moisture. The bag and shields were removed prior to pressurizing the system.

After condensing the liquid fluorine in the 10-gallon test apparatus, it was transferred through the 0.25 inch diameter line immersed in a liquid-nitrogen bath (to maintain the density of the liquid fluorine during the transfer) into the manifold located on the test rack. The manifold was also immersed in a liquid bath and then impinged onto each sample separately. Approximately 3 liters of liquid fluorine were condensed from each gas cylinder. Each sample was jet-impinged with approximately 500 cubic centimeters of LF_2 per test (1/16 inch orifice, 5 to 8 seconds, at 50 psig).

E. Results

Table III tabulates individual test results. It indicates the specific reaction, such as immediate fire, delayed ignition time, degree of fire, no reaction, etc.

VIII. CONCLUSION

The results of the chemical compatibility tests indicated that, of the forty-seven materials tested, only four supported elastomers, ten unsupported elastomers, and three fluorocarbons proved to be compatible.

It is not known whether the method of polymer application or compounding made the difference in compatibility. Spectroanalysis did not reveal enough differences in polymer formulation or molecular arrangement to indicate specific differences between polymers.

Several of the materials, such as butyl over nylon, neoprene over nylon, Buna-N overy nylon, neoprene 89, and Gentex 2, which demonstrated good results in the chemical compatibility tests, caught fire when liquid-impinged.

The following summarizes the results of both the gaseous and liquid tests:

1. Armalon 97-001 material demonstrated the best overall performance to both gaseous and liquid tests.

2. Armalon 97-001G was demonstrated to be chemically compatible, and two samples demonstrated the lowest fluorocarbon permeability rates. However, a third sample had high leakage rates and, when closely examined, pinholes were found. (It was hypothesized that the pinholes were caused when the gold was vapor-deposited onto the film.) Portions of the gold samples caught fire when liquid-impinged.

3. Armalon 97-001A also was demonstrated to be chemically compatible but, when permeation tested, one sample demonstrated excessive leakage rates. (Again, when closely examined, pinholes were found.) The sample caught fire when liquid-impinged.

TABLE III: RESULTS

Sample	Trade Name	Composition	Results
1	Gentex	Al_2-Glass-Neoprene	Caught fire immediately.
2	Wilgard Glove 89 Wilson Rubber Co.	Neoprene	Caught fire. Delayed fire reaction.
3	Du Pont 190-27-3	Butyl-coated nylon	Caught fire immediately.
4	Du Pont Armalon 97-001	Teflon fabric - Teflon FEP film	Caught fire. One end burned. Delayed fire.
5	Du Pont Armalon 97-001G	Same as above 97-001 - gold coating	Caught fire on one side.
6	Du Pont Armalon 97-001A	Same as 97-001G except aluminum coated	Caught fire. Delayed action. Burned quite rapidly once it started.
7	Du Pont Armalon 97-001G	(Retest) Same as Sampel 5	Caught fire around perimeter of sample. Edge of the gold burned and flaked off.
8	Cellulose Acetate	Faceshield, 0.060 inch thick	Caught fire. Delayed reaction. Once started, it burned up approximately 2 inches of faceshield.
9	Wilgard Glove	Neoprene	Caught fire. Delayed action.
10	Du Pont 5009	Neoprene over nylon	Caught fire immediately.
11	Du Pont 5085	Buna-N over nylon	Caught fire immediately.
12	Acrylic	Faceshield	Caught fire immediately.
13	Du Pont Armalon 97-001G	(Retest) Same as Samples 5 and 7 with butyl rubber seam	Seam caught fire immediately with vigorous burning.
14	Cellulose Acetate	(Retest) Faceshield	No reaction.
15	Du Pont Armalon 97-001	Same as Sample 4	No reaction.
16	HT-1-FEP-Gold	Polyamide-FEP film plus gold deposition	Violent fire immediately.

TABLE III: RESULTS (Con't.)

Sample	Trade Name	Composition	Results
17	FEP film, 0.005 inch thick	Faceshield	No reaction.
18	FEP, 0.020 inch thick	Faceshield	No reaction.
19	Gra-lite	Cotton-coated, both sides with PVC	Caught fire immediately.
20	Du Pont Armalon 97-001	(Retest) Same as Samples 4 and 15	No reaction.
21	Du Pont Armalon 97-001	This sample had been exposed to GF_2 for 24 hours prior to liquid testing.	No reaction.
22	FEP film, 0.020 inch thick	Faceshield Same as Sample 18	No reaction.
23	Cellulose Acetate	Faceshield Same as Samples 8 and 14	No reaction.
24	Gra-lite	(Retest) Same as Sample 19	Caught fire immediately.

Note: Colored movies were taken of each test.

MOLLOY, ROCKETDYNE: Could you tell me, how long you could have an exposure like you are talking about, with your suit, before the corrosive qualities of fluorine would penetrate and further, what kind of a situation would there be where someone would be exposed and use a suit like that?

PLUMB: The material has been subjected to 24 hours to 100% gaseous fluorine with little or no deterioration of the material. To your second question, I just can't believe that you people who have been test engineers for a number of years don't have situations out on your test pads where you're going to go out there and check something. You're not going to abort a test because you have a certain area that you don't want to stop. I conceive many areas such as in transfer from the truck to the storage area; it could be in making and breaking lines after testing; around cleaning type operations; I can think of 101 different operations in which you might get exposure to gaseous fluorine.

MOLLOY: Where would you get the impingement that you're so worried about with a suit of this type? Certainly nobody would expose themselves to this.

PLUMB: Certainly they wouldn't, but they do. I was a test engineer for quite a few years before I got in safety and I can conceive of many different operations where you close off a valve at a point. You're pressurized to that point, you may not be entirely through your system, but I can't conceivably think you're going to abort a test because you're live up to a point.

SEWARD, NASA: What was the optimized material you selected for your suit?

PLUMB: It was a teflon film with a floralastimer, with a teflon fabric, its a multi layer and is identified as P101S.

PRYOR, JPL: How did you armor your seams, or did you armor the seams?

PLUMB: That's a good question. Its an overlaped seam and its sewn and there's a strip of the material of the elastimer over the top of the seam and its done both inside and outside.

PRYOR: Is this an electrical welded seam.

PLUMB: Strictly thermal heat.

LANDAU: What's the cost of this suit?

PLUMB: About $3,000.

GOOKIN, AFRPL: Would you discuss please any environmental test you might have run with the suit, to temperatures and humidities?

PLUMB: It was not run to any temperature or humidity. All the tests conducted were at room temperature, there was no elevated temperature, and the humidity was anywhere from 30 to 70%.

GOOKIN: Would you like to hazard a guess as to what might happen if you were operating in 110 or 120°?

PLUMB: I'd say nothing would happen.

GOOKIN; Do you think it would be comfortable?

PLUMB: All you have to do is to place a vortex tube and you can control this suit. We're using vortex around 1500° F. in which people are standing over hot platens and around things of this nature. We're using regular plant air with a vortex tube and we're controlling the air within plus or minutes 1°F.

FAULT TREE ANALYSIS
AS APPLIED TO MISSILE SYSTEMS

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Abstract

A method for predicting potential hazards to equipment, facilities and personnel resulting from malfunctions within a missile system is proposed. The method is described in a brief form in order to demonstrate the basic components and operations involved. This method for predicting potential hazards can determine the cause of an undesired event, can be used as a safety tool, can serve as an analyzing technique, can predict possible failures and can be used economically and effectively to determine means for minimizing potential hazards.

FAULT TREE ANALYSIS AS APPLIED TO MISSILE SYSTEMS

Introduction

During the last several years, the efforts of engineers to determine an effective means for predicting trouble in missile systems, for predicting accidents if you will, have cost tremendous sums of money to say nothing of the manpower expended on this task. Although good results have been obtained from various other prediction methods, the concept known as Fault Tree Analysis is rapidly gaining favor in the opinion of analysts concerned with System Safety. The Fault Tree Concept may not yet be the final answer, but its use is proving to be extremely valuable in the areas of Reliability and System Safety. The purpose of discussing the Fault Tree Analysis process in conjunction with missile systems is to point out the advantages of employing such a concept to detect the presence of potential hazards in missile systems.

Objectives

The Fault Tree Analysis concept is employed in System Safety in order to predict the presence of a potential hazard in a complex missile system. However, the same type of analysis has been used after the fact, that is, to determine the cause of an undesired event which has resulted from an unknown or undetermined hazard. The prediction process is used to a far greater extent than the determination process. We may therefore consider that the Fault Tree concept is useful to missile engineers to (1) predict the cause of potential hazards, or (2) determine the cause of an accident.

Definitions

In order that a subject of this type be meaningful, it is usually wise to define some of the terms used.

A properly used Fault Tree is a "Tool to prevent the occurrence of an undesired event".[1]

[1] Proposed revision to MIL-S-38130

A System is used in reference to a missile system and is defined as "An integrated relationship of components aligned to establish proper functional continuity towards the successful performance of a defined task or tasks."[2]

A hazard, in relationship to System Safety, is any condition which could cause a mission to malfunction in such a manner that equipment, facilities or personnel are endangered.

System Safety may be defined as "the optimum degree of safety within constraints of operational effectiveness, time and cost, attained through the specific application of system engineering throughout all phases of system development"[3], and amplified to the extent that system safety is vitally concerned with the ability of the end item to be manufactured, tested, shipped, operated, maintained or otherwise used with minimum hazards to equipment and personnel through the design to target sequence.

Preparation of a Fault Tree

Let us construct a Fault Tree for a missile Flight Safety System similar to that used in the early phases of POLARIS, PERSHING and MINUTEMAN for the protection of equipment, personnel and associated facilities. It may be remembered by some that the designation of POLARIS was changed from IRBM, Intermediate Range Ballistic Missile, to IBRM, In the Banana River Missile, because of the malfunction of its destruct system.

The first step in preparing a Fault Tree is to gain knowledge of the symbology employed and the manner in which the flow diagram is generated. Generally used symbols as shown in Figure 1 indicate the method by which events are either consolidated or isolated. The AND gate indicates that two or more events must occur in order to proceed farther along a particular tree branch. The OR gate signifies that either of several events may occur in order to proceed. A circle depicts a basic component fault influencing an AND or an OR gate resulting from an individual erroneous condition and requires no further development. The hexagonal symbols indicate connections between causes and effects

[2] AR 320-5 Dictionary of United States Army Terms

[3] Proposed revision to MIL-S-38130

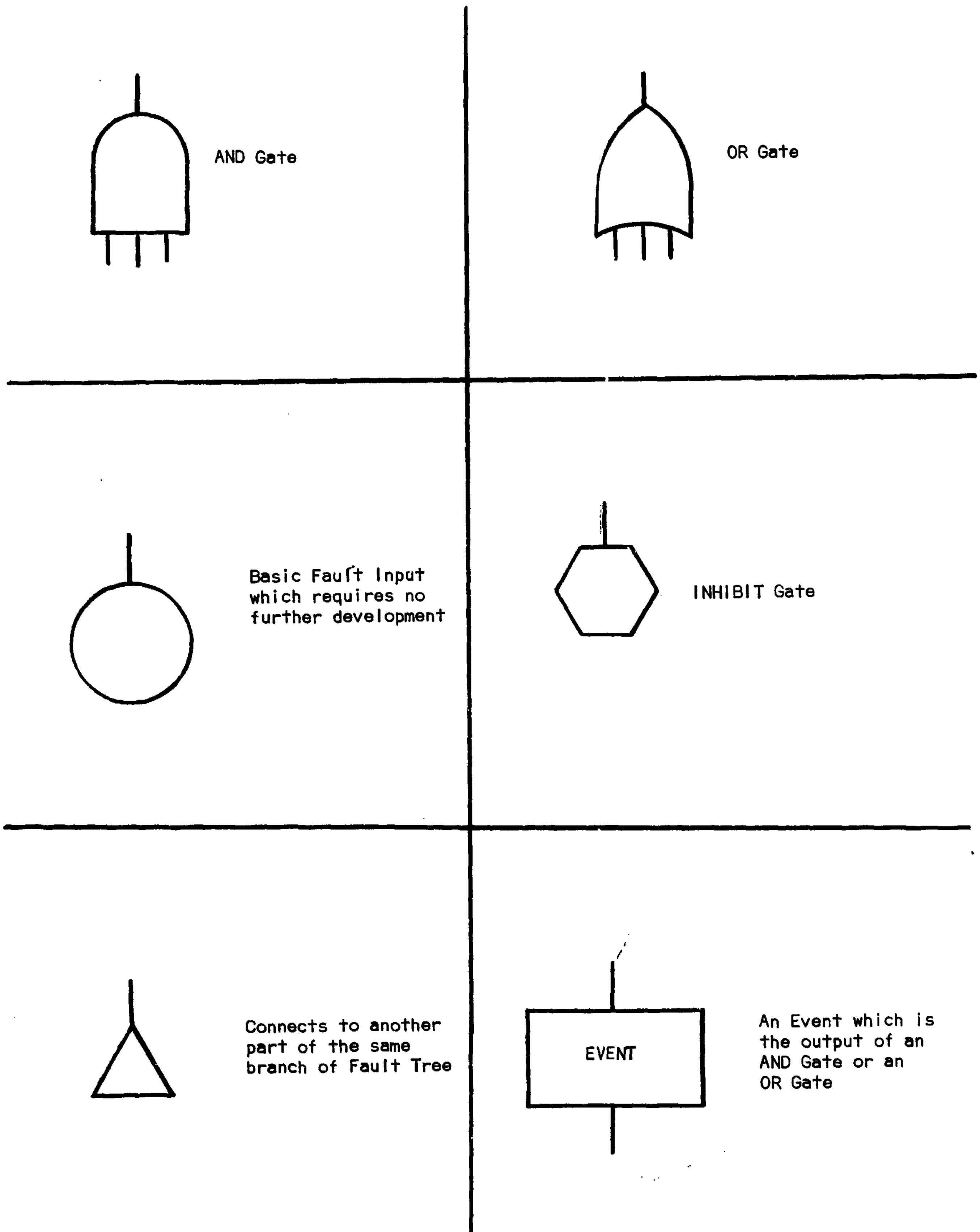

AND Gate
OR Gate
Basic Fault Input which requires no further development
INHIBIT Gate
Connects to another part of the same branch of Fault Tree
EVENT
An Event which is the output of an AND Gate or an OR Gate

Fig. 1

in branches of a complex fault tree. They are essentially a form of an AND gate called an INHIBIT gate. A rectangle signifies an event which is usually the output of an AND or an OR gate. Other symbols are also used to denote particular conditions which may be influential in this type of analysis. Figure 2 shows the skeleton of a typical fault tree in order to indicate how the symbols are used and to explain the sequence of events. Initially, an undesired event is selected for investigation. Other events which are capable of causing the basic undesired event are then introduced into the flow pattern. Then, by proper use of the symbols, a determination of the most probable contributory event is made.

The next step in the preparation of a fault tree involves the collection of basic data which is required to construct the tree branches. This data may be in the form of fundamental designs, field event reports, engineering drawings, actual hardware or any other items which could contribute to the cause of the undesired event.

The third step consists of utilizing the data collected in Step 2 for the actual construction of the fault tree. Some trees may be simple ones because of the number of modifying or contributing events which will cause the undesired event. Most fault trees are rather complex in that during their construction, one will find apparently unrelated events which actually influence mutually dependent events, and which in turn contribute to the undesired event.

Step Number 4 discloses a somewhat controversial aspect of the Fault Tree Analysis Concept. If a complete analysis is to be conducted, a technique is used which is based on the application of Boolean algebra and its symbology, processed and programmed into a computer, the output of which becomes a numerical probability of the occurrence of the undesired event. Since this process becomes a costly one, many fault trees are constructed for a magnitude determination based on Critical Path philosophy rather than on the determination of a number. This approach to the analysis assumes worst case conditions via tree branches which clearly indicate producible errors from which reasonable estimates can be obtained

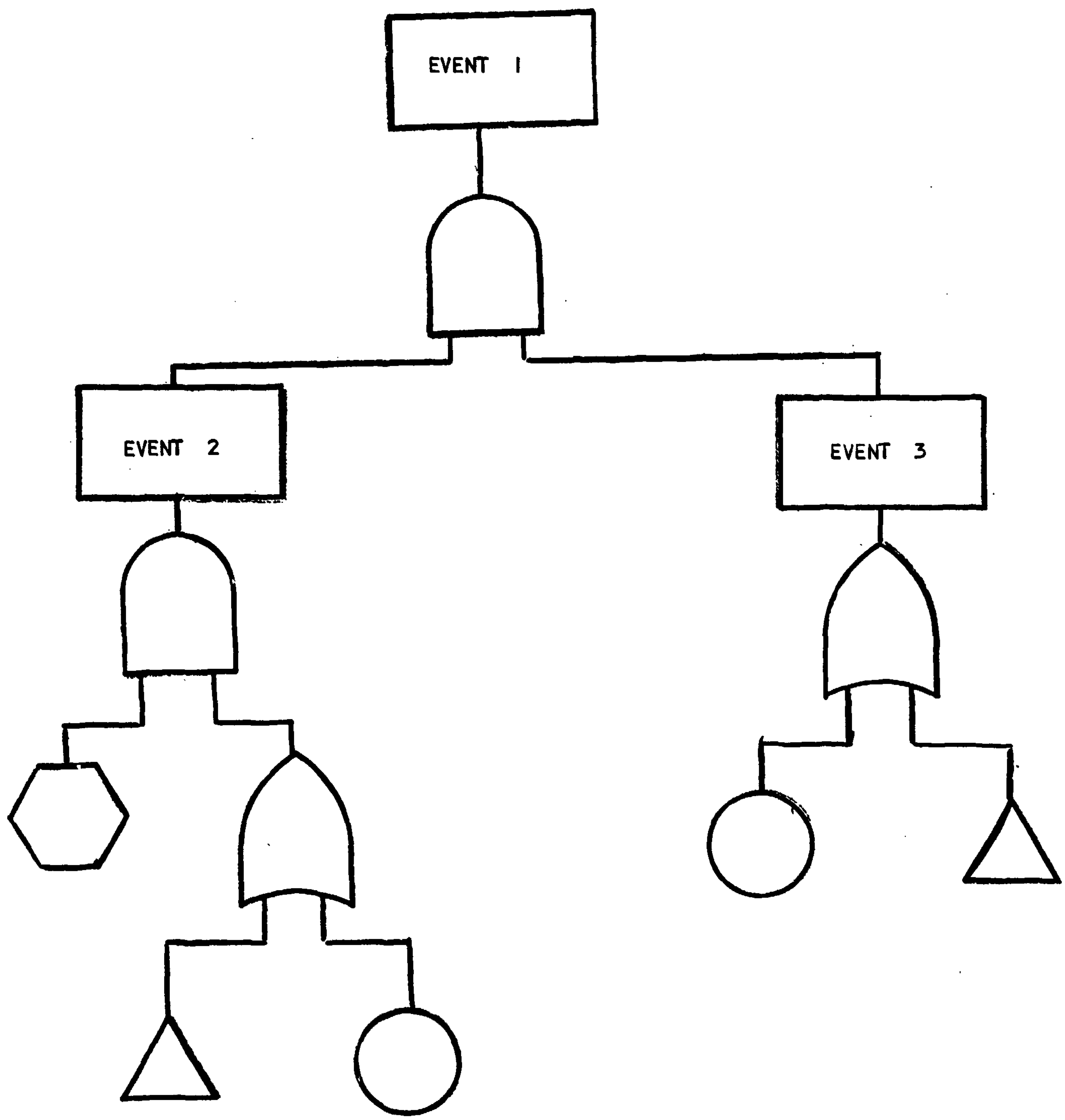


Fig. 2

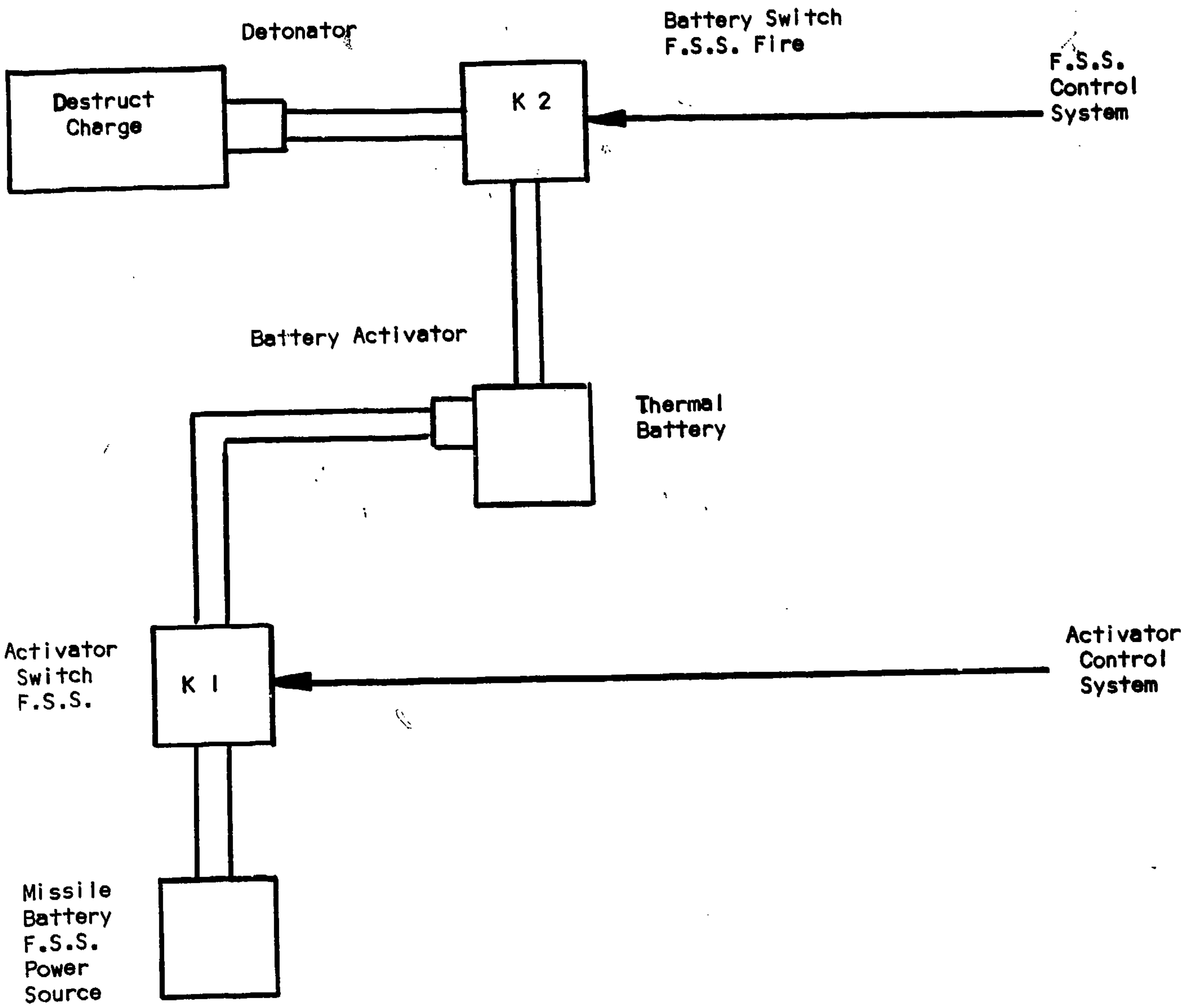

Detonator
Battery Switch
F.S.S. Fire
F.S.S.
Control
System
Destruct
Charge
K 2
Battery Activator
Thermal
Battery
Activator
Switch
F.S.S.
K 1
Activator
Control
System
Missile
Battery
F.S.S.
Power
Source

Fig. 3

as to the probable cause of the undesired event. The latter method of fault tree analysis is not as complete or as rigorous as the computer method, but it is satisfactory in obtaining a solution to less complex fault tree problems.

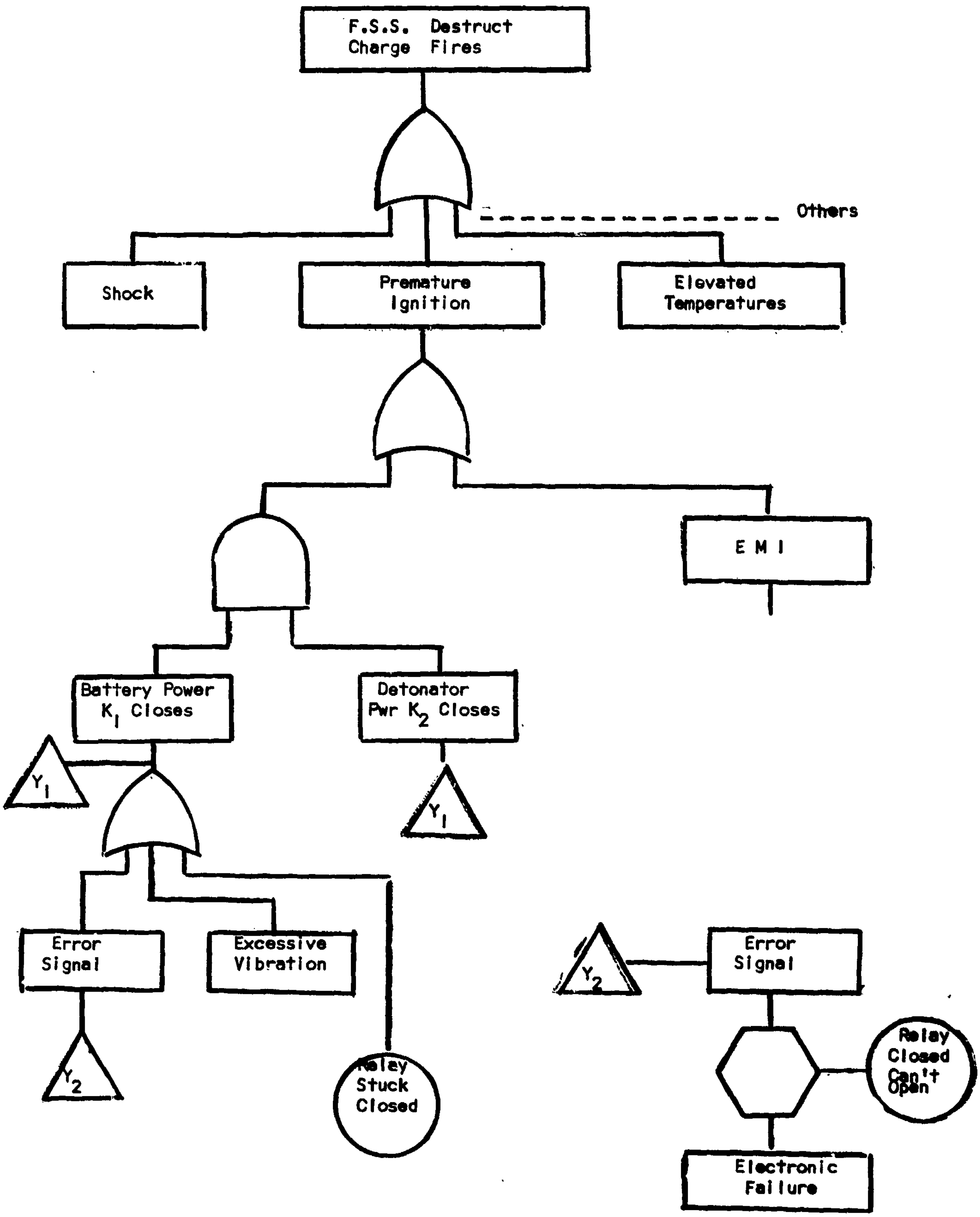
The fifth step may be used in support of the Critical Path solution. This procedure involves the conduct of a Failure Mode and Effects Analysis in conjunction with each item or component in a tree branch which may contribute to the undesired event. By using the Critical Path concept in relation to the worst case analysis of a particular contributing event, a determination of the magnitude of the potential failure may be estimated.

The last step to be taken before construction of the tree is an analysis of the Fault Tree itself. One must ask himself the question, "Have I included all the possible contributory events which might affect the undesired event?" "Have I become too detailed in building my tree; have I gone beyond or below those events which may cause the undesired event?" Normally, as the Fault Tree is constructed, the tendency is to exclude minor events because they do not appear to affect the solution. On the other hand, like a well-built TV set, redundancy of fine adjustments may cause one to include duplicate items where the failure of one will not affect the operation of the system. One must be careful to use the proper symbols and to ascertain that the inputs to AND or OR gates comply with the rules of the analysis.

In System Engineering, the use of analytical logic diagrams and math models is a well accepted practice. The Fault Tree Concept, properly employed in conjunction with the above functions, will not only produce a more complete picture for determining Reliability and Safety factors, but it can predict potential hazards during the design to target sequence thus providing a basis for corrective action before an undesired event occurs.

Typical Fault Tree

Figure 3 is a block diagram for a typical power source and firing


F.S.S. Destruct Charge Fires
Others
Shock
Premature Ignition
Elevated Temperatures
E M I
Battery Power K_1 Closes
Detonator Pwr K_2 Closes
Y_1
Y_1
Error Signal
Excessive Vibration
Y_2
Relay Stuck Closed
Y_2
Error Signal
Relay Closed Can't Open
Electronic Failure

circuit for a missile Flight Safety System destruct charge. It consists of the charge and its igniter, the battery switch K_2 which is the Flight Safety System fire switch, an external F.S.S. control system and the thermal battery from which power is derived to activate the charge detonator. Next, we have the thermal battery activation device which is initiated by the activator switch K_1, or the F.S.S. safe and arm switch with its external S&A control circuit, and powered by a missile battery. Note that both K_1 and K_2 switches must function in order to detonate the destruct charge. Let us try to predict which elements would have an effect on causing the destruct charge to activate inadvertently while the missile is still on the ground launcher. Figure 4 illustrates the first steps in the construction of a simple hypothetical fault tree which should help us find one of the potential hazards associated with this system.

Let us assume that hot wire initiators are employed. We can then further assume that an unplanned or inadvertent firing can be caused by elevated temperatures, shock, premature ignition, or by any one of several other methods. We label these possible causes as events, any one of which might contribute to a condition necessary for firing the F.S.S. destruct charge. For illustration purposes, let us investigate possible causes of premature ignition. It appears that either EMI OR switching can be a real contributor. Since the power side of our tree lends itself as a good example of Fault Tree procedural tactics, we notice that the inputs to the OR gate are an event and an AND gate. The AND gate indicates that two events must occur as inputs to the gate in order to obtain an output. In our case, these two events are the closing of the missile battery power switch K_1 and the closing of the detonator battery power switch K_2, without which a premature ignition could not occur as the result of action in this branch of our tree. The triangular input symbols to the K_1 - K_2 events indicate that these switches are influenced by other events, such as control circuits, within the same branch of the tree. Let us now consider the reasons for switch K_1 closing. Any of three actions, introduction of an

error signal, OR excessive vibration, OR a relay stuck in the closed condition, can cause switch K_1 to close. The circle symbol indicates that the stuck relay is a basic fault input which requires no further development. In determining the cause of an input error signal to the OR gate, we use the triangular symbol Y_2 to transpose action within this tree branch to a roomier area in which to continue our tree construction. The hexagonal INHIBIT gate input consists of undefined and general electronic failures, and its output is restricted to the error signal with which we are concerned. The elliptical symbol indicates a condition which allows an input-output fault to be restrained or inhibited as the reaction transits the gate. Thus, from a source of perhaps several electronic failures, an error signal makes its presence felt in the left hand tree branch. We are now faced with the possibility of a relay stuck in the closed position OR excessive vibration OR an error signal as the cause of switch K_1 closing prematurely. Next, we investigate the problem of excessive vibration and we find that a report from Reliability Test informs us that the switch K_1 tested well within the specification limits during its last checkout. The stuck relay is a basic fault, so we will attribute a faulty operation of K_1 to an error signal. Again we note that both K_1 and K_2 must malfunction to cause a premature ignition. We therefore investigate K_2 in the same manner in which we analyzed K_1. From the fault tree we note that EMI OR the switches can cause a premature ignition so the EMI branch must also be analyzed. Finally, we ascertain that this particular circuit has a high reliability and the probability of a potential hazard occurring is very low. On the other hand, if, from our diagram, K_1 and K_2 could be initiated simultaneously, we could then take steps to correct this situation thus eliminating the cause of a potential hazard. This abbreviated discussion indicates what can be accomplished by a Fault Tree Analysis using the critical path method.

Summary and Conclusions

Although conclusions are difficult to determine as a result of this

very brief discussion of the Fault Tree Concept, we can define a few.

First, the Fault Tree concept will give us an idea of the cause of an undesired event within a system.

Second, the Fault Tree can be used as a tool for improving the Safety of a system.

Third, the Fault Tree technique provides a useful method of analyzing a system.

Fourth, the Fault Tree will allow us to predict a possible failure and to take the necessary precautions to avoid the catastrophic effects of a failure.

Fifth, the computerized Fault Tree technique, although more sophisticated and precise than the Critical path method just described, is an expensive process and should be used only in the analysis of more complex Fault Trees.

Sixth, the Critical path analysis is sufficient to determine the general location of the cause of an undesired event, and it will give sufficient information to convince the System Safety Engineer that the area is worth investigating for the removal of a potential hazard.

SYSTEM SAFETY ANALYSIS
by
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Addressing the subject of system safety analysis from the contractor's point of view, I should like to discuss briefly, the following points:

Why Safety Analysis

The Benefits

The Basis for the Analysis

The Prerequisites

Fundamental Approaches

Analysis Selection

There are many reasons for a contractor/manufacturer to perform a system safety analysis concurrently with the development manufacture and delivery of his product.

One obvious reason, in the event the product is military hardware, is a contract requirement levied in the form of MIL-S-38130, SAFETY ENGINEERING OF SYSTEMS AND ASSOCIATED SUBSYSTEMS AND EQUIPMENT.

A second principal reason is the matter of manufacturer's liability. More and more frequently one hears of settlements made on damage suits for personal injuries sustained in connection with the use of various products. Performance of an objective safety analysis could lead to design changes that would preclude the injurious event. Further, it would clearly demonstrate that the manufacturer had not marketed his product without regard to safety.

There are other valid reasons.

The greatest return for the money spent to perform the safety analysis is management visibility. The completed analysis not only represents a quantification of the safety of the system, it is used as a tool to evaluate and measure system changes for impact on established safety levels, and as a basis for management decisions. Once a hazard is identified, either by the analysis or by system use, corrections are based on sound system analysis and one fix is assessed against another to obtain the maximum resolution. This is greatly preferable to making a series of intuitutive changes which may or may not completely remove the hazard.

Examining the basis for the analysis we find that it must be carefully scoped to the system being developed. Obviously, the analysis of a wheel barrow where the main concern is that the wheel might come off would be entirely different from an analysis of a complex weapon system where one is concerned that the war head might inadvertently go off.

The analysis must be both qualitative and quantitative. It should be noted that the quantification of system safety was the most significant factor in establishing system safety as a discipline, on an equal basis with reliability and maintainability.

The analysis selected must provide the required management visibility as described above, or it is pointless to devote the resources and effort required to complete it.

What are the prerequisites for the safety analysis? It must have validity; that is, it must be thorough and comprehensive. It must have feasibility in

that it is within the state of the art. Finally,the cost of performing the analysis must be commensurate with the development and manufacturing costs of the product.

There are two fundamental approaches to performing a system safety analysis. First, there is the component sequential relationship. Typical of this type, is the failure and effect analyses that start at the bottom of the system with a component and traces a single thread failure path through the system. Second, there is the event sequential relationship. Typical of this type, is the Fault Tree Analysis which starts at the top of the system with an undesired event and spreads out through a series of logic gates and events in the form of a tree to encompass the system as a unit. This method will treat interfunctional relationships and cascading faults, and lends itself readily to computerizing.

There are other hybrid methods that can and probably will be developed for special applications as the system safety discipline grows.

I am not prepared at this time to explore the relative advantages and disadvantages of these two methods. Each technique has its use and each satisfies a specific requirement.

The selection of the proper analysis for the task at hand requires a good understanding of the methods available and the amount of management visibility each provides. Secondly, the system complexity and management visibility required for the system then must be identified. Once these steps have been accomplished, it is a simple matter to select the analysis method that best

provides the management visibility required.

Summarizing, we have reviewed the reasons and benefits, the basis and prerequisites, and the methods and selection of the system safety analysis. The specific points that I would like to reiterate and leave with you include:

1. The establishment of a system safety engineering program, which includes an analysis effort, will greatly strengthen the corporate image.

2. It is vital to understand the analysis methods available before a technique is selected and the method must be carefully scoped to the system requirements to be satisfactory.

3. Once the management visibility has been developed through the completed analysis, use it and believe in it. It will serve you well.

A SYSTEMS APPROACH TO HAZARDS ANALYSIS

by

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ABSTRACT

A systems approach is presented for analyzing the potential hazards of a large solid rocket motor from the time it leaves the manufacturing site until it completes a successful launch. The fault tree analysis, a technique successfully being applied for component failure-mode and effect, was modified for hazard analysis. Utilizing the functional flow and logic symbols of the fault tree, a diagrammatic model is constructed which is representative of the relation of the motor with its environment. This model indicates the complex interrelation of the potential accidents and their causes with contributing stimuli, resulting consequences to the motor, and damage to the environment.

INTRODUCTION

The rapid advancement in the state-of-the-art of large solid-propellant rocket technology poses a potential safety problem of serious magnitude to the aerospace industry. The feasibility of using large solid motors, containing from 250,000 to over 4 million pounds of propellant, for future space launches is obviously enhanced by the favorable static-test results of the 156-inch and 260-inch diameter motors. However, these large solid motors envelop enormous quantities of confined energy which, if uncontrollably released, could result in vast destruction of life and property. Realistic quantity-distance requirements for providing protection cannot economically be determined by "conventional" hazard evaluation testing methods. New empirical and theoretical techniques for determining the explosive hazard and damage potential for large motors are under development. Nevertheless, a reliable measure of large motor safety cannot await the lengthy accumulation of operational experience. An alternate approach of logical analysis and system simulation offers some advantages.

The systems analysis approach allows examination of the motor and its interaction with its environment during any or all aspects of its proposed life (e.g., from the time the motor leaves the manufacturing site until successful launch is achieved). Predicted malfunctions and accidents which may affect the motor and consequently the surroundings are analyzed for cause and effect. The appropriate grouping of events in a concise graphical presentation should indicate the criticality of each operation and the damage potential of the system.

This paper presents a systems approach to hazards analysis developed through the modification of the fault tree technique and its application to large solid motors.

SYSTEMS APPROACH TO HAZARDS ANALYSIS

Generally speaking, a system is an assembly of components that are integrated when functioning in obedience to some form of control. This definition is applicable to a rocket motor or the universe. The significance of precisely defining the system for analysis can be readily appreciated.

Systems Safety

Systems safety analysis, as applied in the aerospace industry, has been primarily limited to the functional unit only, such as aircraft, space vehicles, and guidance components. This analysis, usually hardware-oriented, isolates and identifies significant hazardous conditions designed in the system and evaluates the potential risk each poses.

The fault tree technique developed in 1962 by Bell Telephone Laboratories provides for the logical failure-mode-and-effect analysis of functional unit systems. The resulting tree structure derived through logical design and symbolic logic begins with the selection of an undesired event. This event is sequentially analyzed for component failure modes. Once constructed, the fault tree may be expressed mathematically by Boolean Algebra. The final relationship defines the probability of the undesired event as a function of component failure mode probabilities.

The normal application of the fault tree technique, synonymously referred to as systems safety, fails to consider hazards caused by the interaction of the functional unit with its surroundings. The types and extent of damage expected, should a hazard materialize, are also neglected. Obviously, these considerations are very important in a hazards analysis. Henceforth, systems safety as applied to the functional unit and its surroundings will be referred to as systems hazards.

Systems Hazards Analysis

The expanded application of the fault tree technique to systems hazards requires considerable modification. The existing fault tree technique, if used for hazards analysis, results in a logically correct but graphically disoriented presentation. Hazards analyses require that:

A. The system be defined to include the functional unit and its surroundings.

B. The order of sequential analysis be revised.

C. The significance of an event be expressed as a function of its magnitude in relation to the system parameters.

D. A concise logical expression be provided for grouping "effect" events caused by the same single or multiple "cause" events.

E. A concise logical expression be provided for the concurrence of three or more events in any specified number of combinations.

The significance of the modified fault tree techniques will be illustrated by specific application in the hazards analysis of large motors.

The System

If a systems approach is taken with respect to hazards, it is apparent that the system must include the interaction of the functional unit with its surroundings. The system to be analyzed then is defined as the large solid rocket motor and its surroundings. A single cause-effect analysis problem is shown in Figure 1. A comprehensive analysis of systems hazards must consider (a) the entire life cycle of the motor from the time it leaves the manufacturing site until it completes a successful launch, (b) modifications to the rocket motor by the various operations, and (c) the effect of sequential accidents. The contents of such a system are dynamic and may be considered as a variable function with four degrees of freedom—location, magnitude, operation, and time.

Although many simplified approximations will have to be made in order to simulate the system mathematically, the initial graphic analysis should portray the true system. The graphic analysis may thus highlight the significance of dependent variable functions and/or their approximations.

Order of Sequential Analysis

Since the life cycle of a functional unit is operationally dependent, the operations were selected as the initial basis for analyzing and portraying the system. The life of the rocket motor was described by the following operations; handling, transportation, storage, prelaunch operations, and launch.

The normal sequence for fault tree construction is to select a significant undesired event for analysis. Typical fault tree applications select a major accident, e.g., a plane crash, as the undesired event.

The hazard analysis begins with an identification of all the potential accidents that are considered reasonably probable for each of the operational modes. This constitutes a level in the middle of the hazard tree as shown by the sequence of hazard analysis in Figure 2. Since actual accident experience with large solid motors is not available, previous experience with other missiles, propellants, explosives, and the operational mode, coupled with an analysis of the proposed operational equipment and procedures, provided a basis for classifying the types of accidents that can be expected to occur. During handling at the launch site, dropping or toppling of the motor, lightning, explosion in the surroundings, and fire in the surroundings are representative of accidents that are considered credible.

For any particular accident, the usual fault tree approach would be applied to analyze the accident causes. In its general form, an "explosion in the

FIGURE 1. TYPICAL CAUSE—EFFECT ANALYSIS PROBLEM

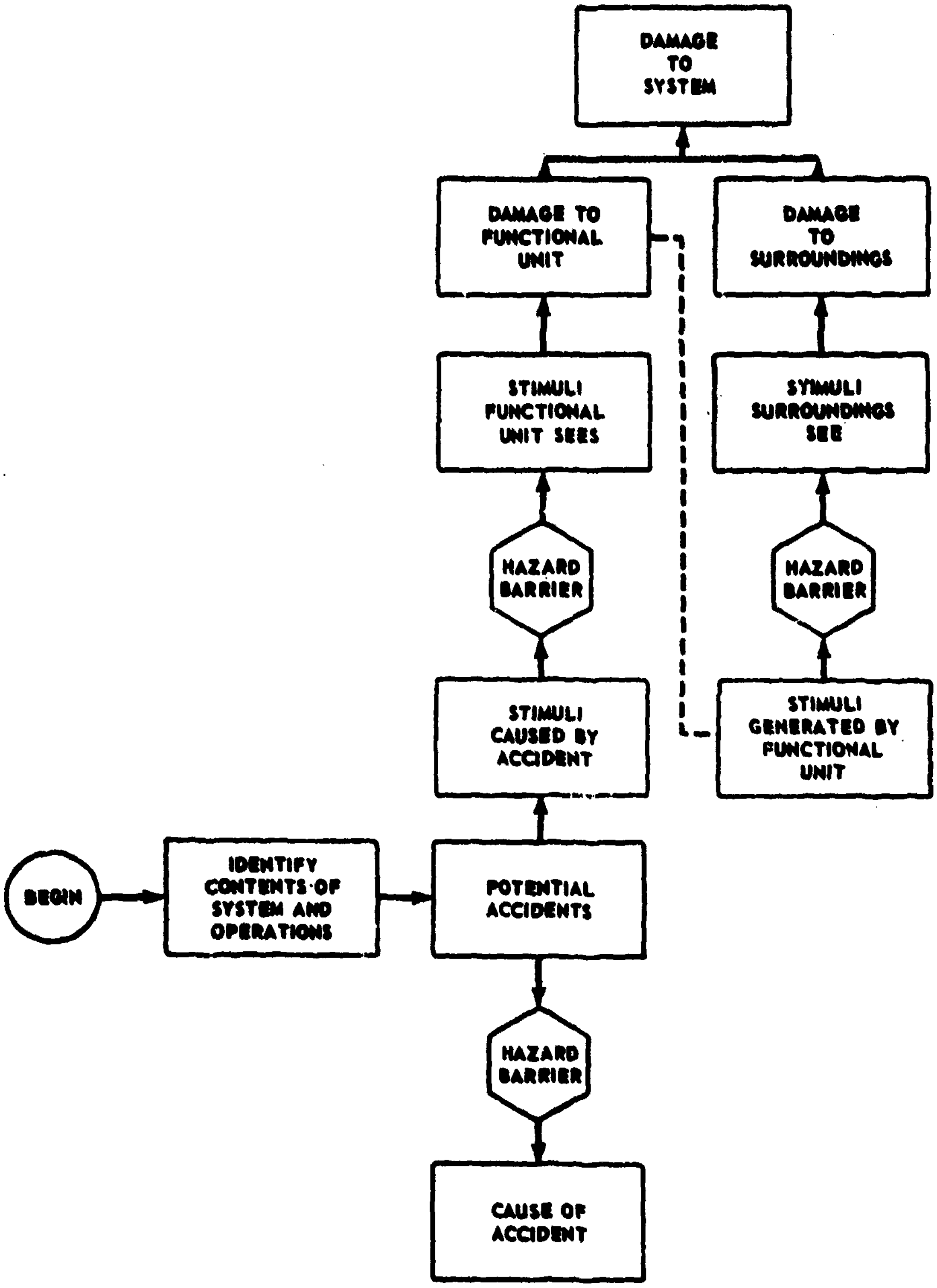

FIGURE 2. SEQUENCE OF ANALYSIS FOR HAZARDS

surroundings" would be defined as the undesired event. Personnel error, equipment failure, unusual natural phenomena, sabotage or vandalism are activities that may occur in the environment to cause the undesired event. For a specified environment an "explosion in the surroundings" could more accurately be described as explosion of a diesel engine on a transporter drive unit, a liquid petroleum gas tank truck on the highway, ammonium nitrate in a rail boxcar, or an upper stage liquid motor. Since accident prevention is a primary safety consideration, some environments may warrant an exhaustive investigation of accident causes in an effort to minimize the possibility of the accident's occurring. The use of the fault tree symbols to depict the motor—environment relationship of potential accidents and their causes is shown in Figure 3.

In constructing the system upward, the accident effect for each potential accident is hypothetically described to portray the sequence which could cause "damage to the system." This segment of the analysis may also provide evidence to substantiate the incorporation of safety features which could provide additional protection to the motor, such as protective barricades. It is at this point that departure from the normal fault tree structure becomes necessary.

Functional Dependencies

The occurrence of an event and its significance in a hazards analysis is functionally dependent upon the contents of the system, the time and the place. The dependency of event occurrences on system variables may be included through the use of Conditional Inhibit gates. Accidents which can subject the motor to similar stimuli are grouped to more clearly indicate the significance of the motor parameters in determining the consequences from various stimuli magnitudes. Environmental factors, such as the interlying geography and distance between the accident and the rocket motor which would influence the magnitude of stimuli to which the motor may be subjected, are appropriately included as shown on Figure 4. If the functional dependencies are not known at the time of system simulation, approximations may be inserted.

Tree Junction

Existing fault tree construction utilizes a Transfer symbol △ to insert an event previously analyzed in another portion of the structure. No provision is made for grouping events which have a common cause or combination of causes. Consequently a concise picture of all the results that can occur because of a particular hazard or component failure is not provided.

Inverting existing logic symbols and utilizing them as tree junctions proved to very useful. The Inverted Tree Junction limits the repetitive use of Inhibit gates and Transfer symbols. The emphasis on grouping and the

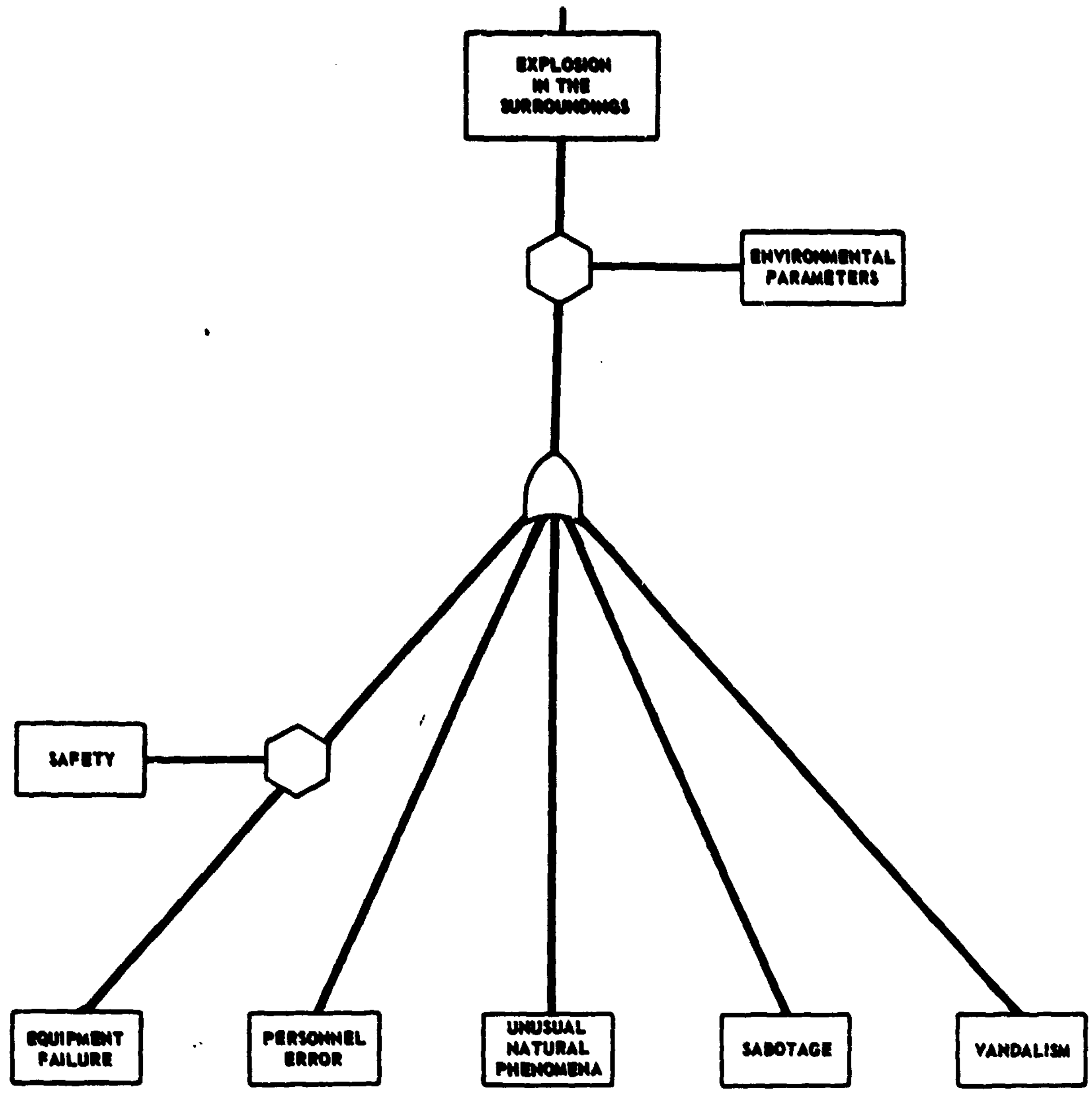

FIGURE 3. FAULT TREE FOR A POTENTIAL ACCIDENT

provisions for its logical representation assist in controlling the haphazard growth of fault trees and also provide for a more specific analysis of the inter-relationship of events.

The usefulness of the Tree Junction is clearly illustrated by presenting lightning, explosion in the surroundings, and fire in the surroundings and their combinations as possibilities for providing magnitudes of heat in various combinations with flame, shock, and blast. The Tree Junction in Figure 5 represents

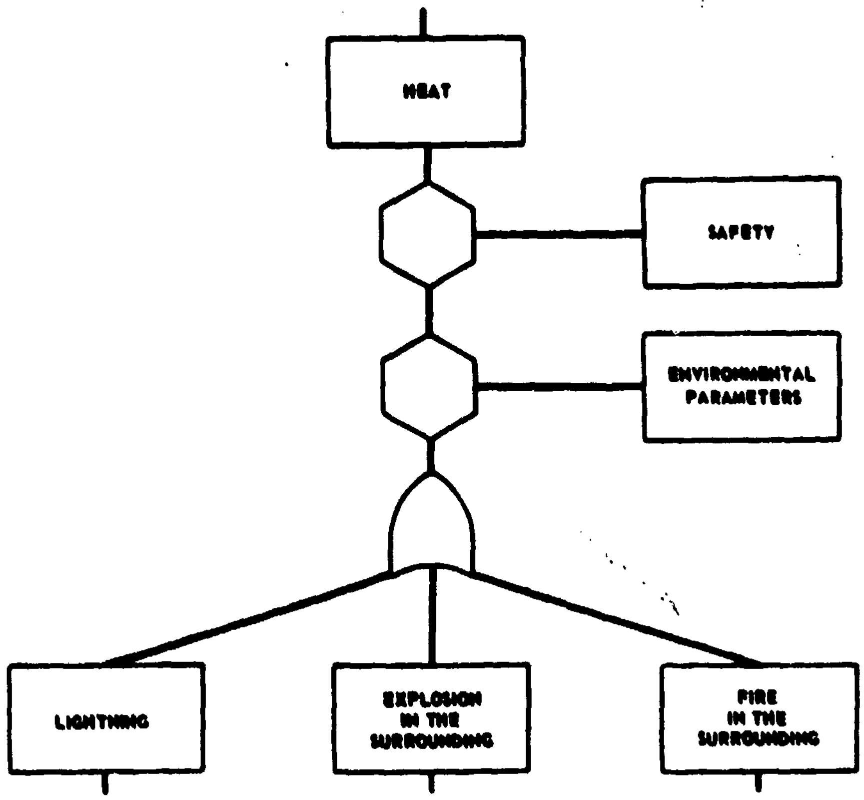

FIGURE 4. FUNCTIONAL DEPENDENCY ON ENVIRONMENT

the relation between the seven combinations of the three cause events and fifteen combinations of the four results events. This relationship is also represented by the matrix in Table I. As illustrated in Figure 6, constructing a normal fault tree structure to represent this matrix is extremely cumbersome and proved to be of little value once it was completed.

Restrictive Or

Existing fault tree logic gates and symbols do not provide adequate control over the restriction of event combinations when more than two events are involved. This becomes apparent when the seven combinations of three events (A, B, C, AB, AC, BC, ABC) are examined with respect to existing logic. The logical Or expresses the possible existence of any or all of the seven combinations. The logical And restricts all the combinations except one (ABC). The Exclusive Or allows only three possibilities (A, B, C) but not at the same time.

The need for presenting other groups of combinations increases as the number of events considered increases. The Restrictive Or gate, which combines the logical Or and Inhibit gates, was generated for this purpose. The

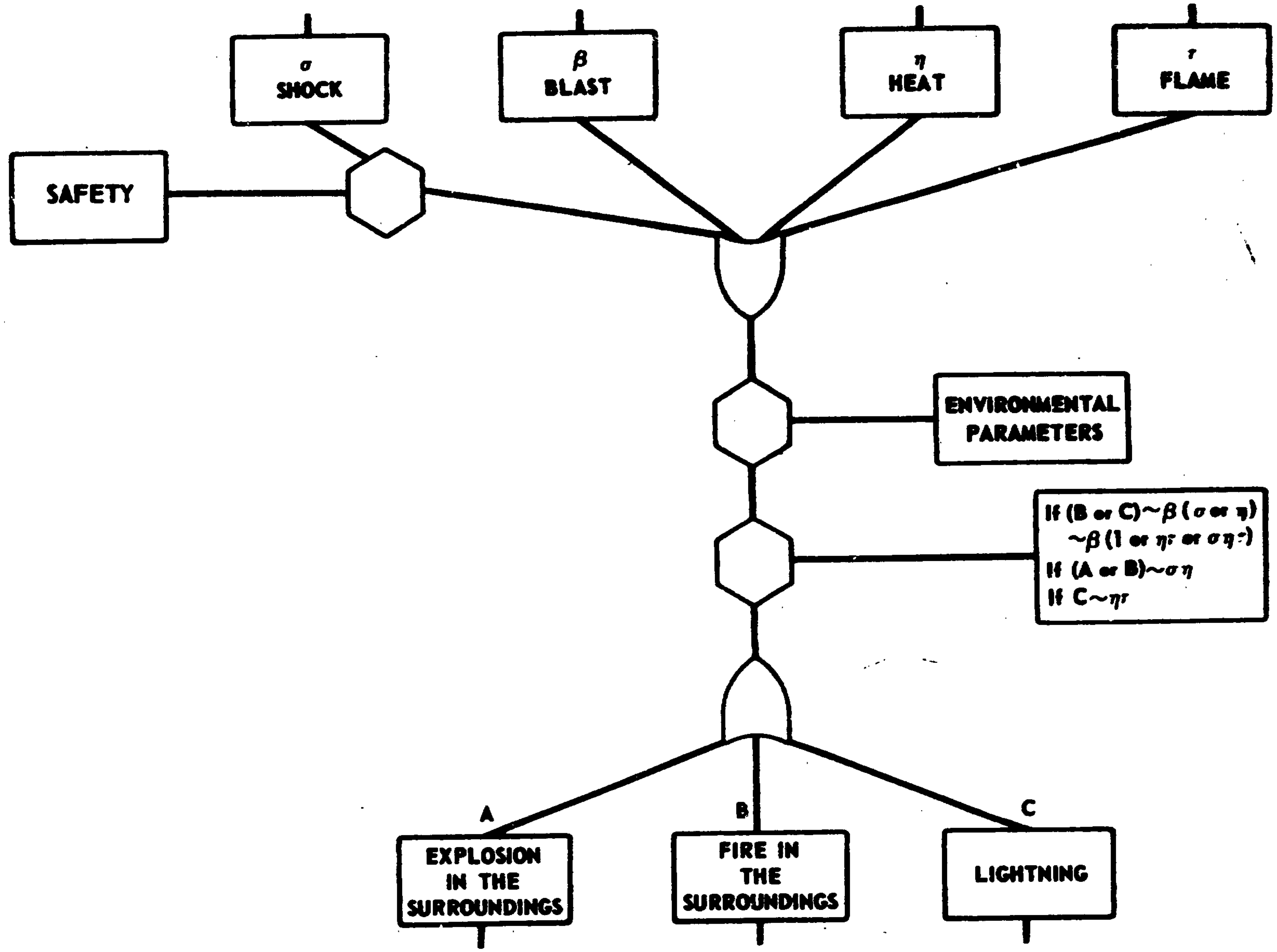

FIGURE 5. TREE JUNCTION FOR ACCIDENT—STIMULI RELATIONSHIPS

Table I

MATRIX FOR ACCIDENT—STIMULI RELATIONSHIPS

	A	B	C	AB	AC	BC	ABC
β	Y	N	N	Y	Y	N	Y
$\sigma\beta$	Y	N	N	Y	Y	N	Y
$\eta\beta$	Y	N	N	Y	Y	N	Y
$\sigma\eta\beta$	Y	N	N	Y	Y	N	Y
η	Y	Y	Y	Y	Y	Y	Y
$\sigma\eta$	N	N	Y	N	Y	Y	Y
$\eta\tau$	Y	Y	N	Y	Y	Y	Y
$\sigma\eta\tau$	N	N	N	N	N	N	N
$\beta\eta\tau$	Y	N	N	Y	Y	N	Y
$\sigma\beta\eta\tau$	Y	N	N	Y	Y	N	Y
σ	N	N	N	N	N	N	N
$\sigma\tau$	N	N	N	N	N	N	N
τ	N	N	N	N	N	N	N
$\beta\tau$	N	N	N	N	N	N	N
$\sigma\beta\tau$	N	N	N	N	N	N	N

LEGEND

Accidents: A = Explosion in the Surroundings

B = Fire in the Surroundings

C = Lightning

Stimuli: σ = Shock, β = Blast, η = Heat, τ = Flame

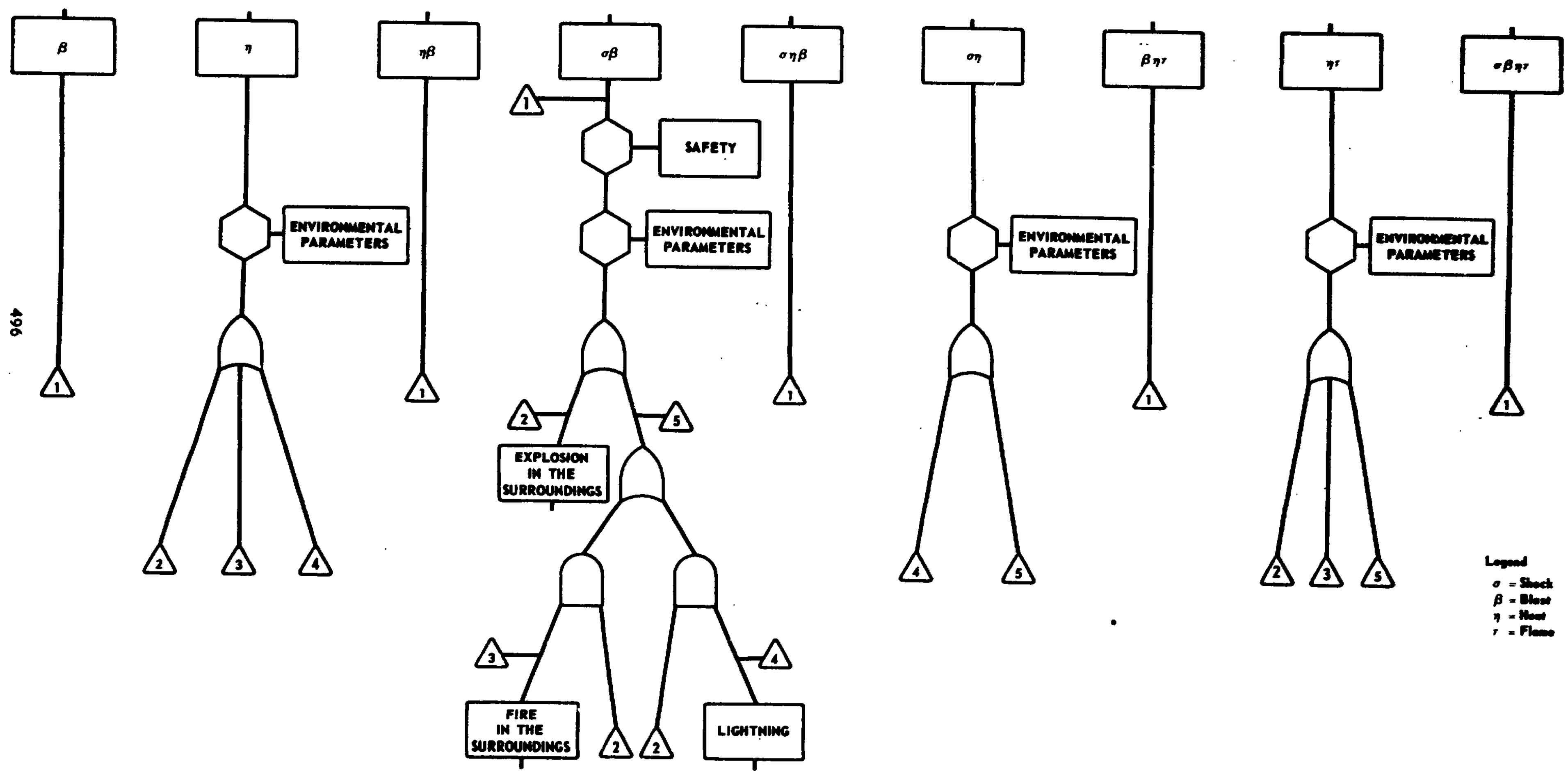

Figure 6. NORMAL FAULT TREE FOR ACCIDENT – STIMULI RELATIONSHIPS

Restrictive Or would exclude combinations considered to be unreasonable as indicated in Figure 7.

Depending on the sensitivity of the motor to magnitudes of stimulus or stimuli produced by an accident, certain consequences can be expected to occur to the motor. Figure 8 portrays this interrelationship for the general accident "explosion in the surroundings." If, for example, the blast effect produced by an "explosion in the surroundings" results in a shock peak pressure which exceeds 80 kilobars, the motor may detonate if it is above the critical diameter or the burning surface area is much larger than planned for. An expression of the sensitivity characteristics of the motor which could relate the structural integrity and initiating mechanism of the propellant to certain basic chemical, physical, and kinetic factors would provide an analysis technique adaptable to the hazard evaluation of any rocket motor.

Knowledge of certain motor parameters and environmental factors is also required to determine the extent and severity of damage to the environment from the reacting propellant as shown in Figure 9. To establish the damage potential

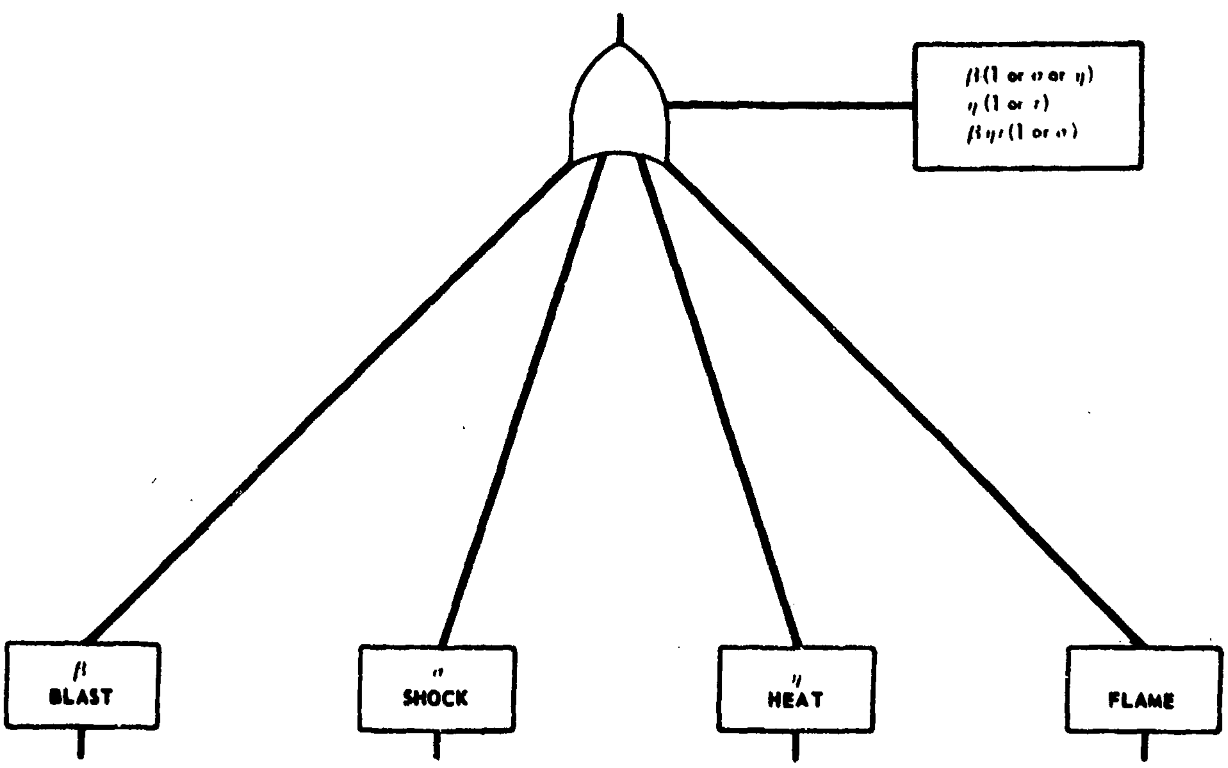

FIGURE 7. RESTRICTIVE CONDITIONS ON STIMULI CAUSED BY "EXPLOSION IN THE SURROUNDINGS"

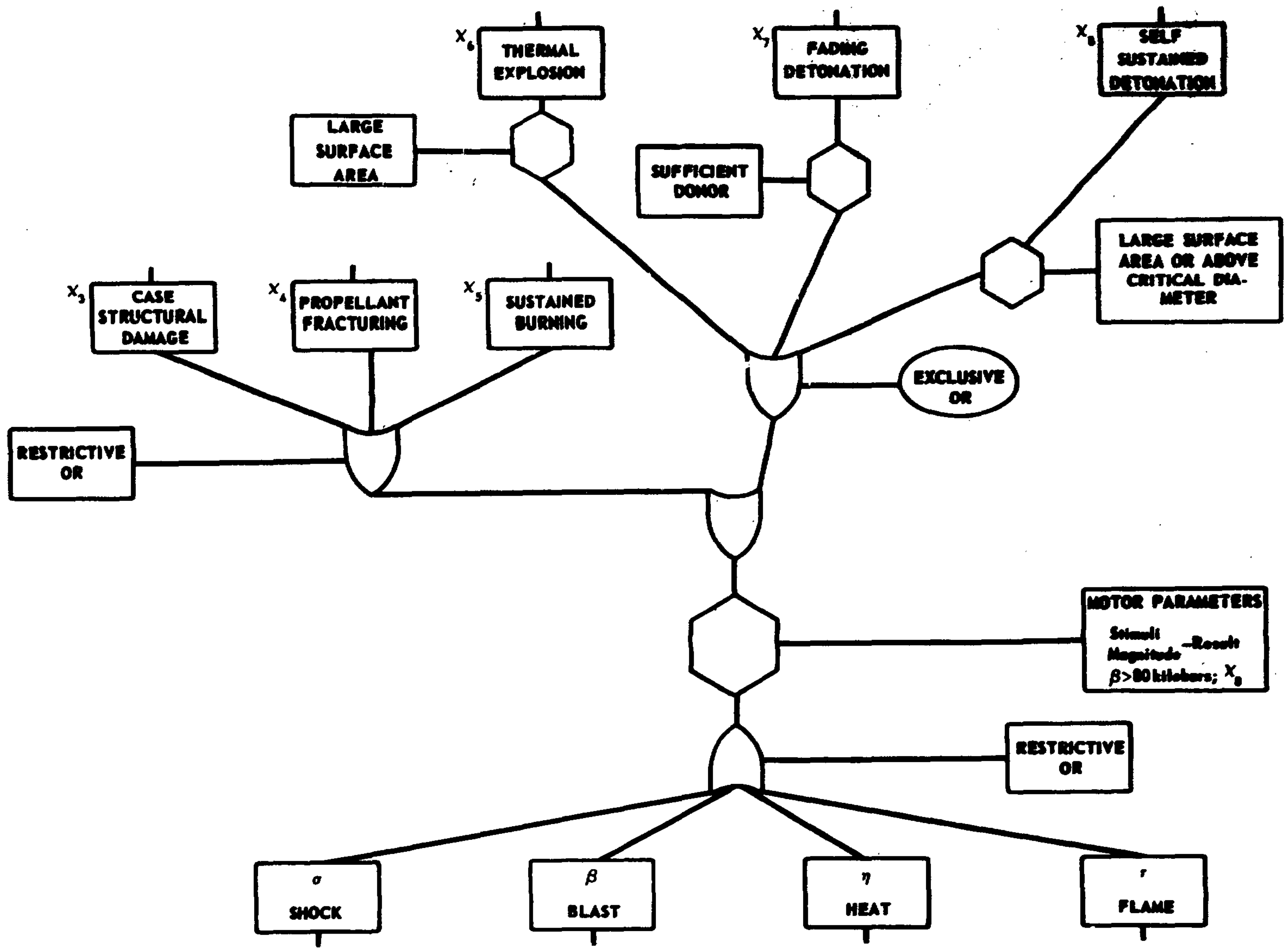

FIGURE 8. MOTOR CONSEQUENCES FOR ACCIDENT, "EXPLOSION IN THE SURROUNDINGS"

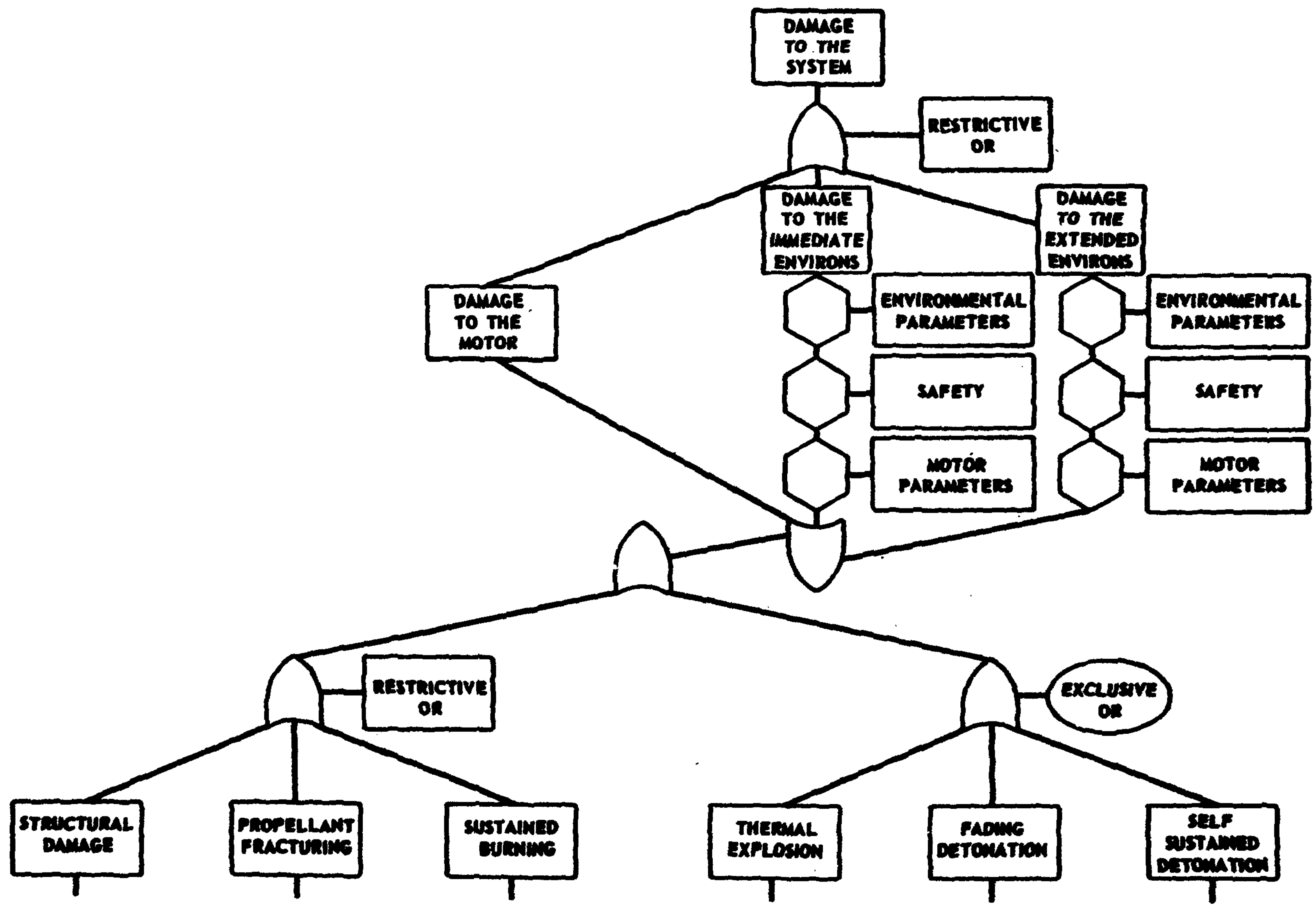

FIGURE 9. DAMAGE POTENTIAL FOR ACCIDENT
"EXPLOSION IN THE SURROUNDINGS"

for deflagration, explosion, and detonation, information concerning the energy release rate, blast effects, extent of fragmentation and fire that may be produced must be known. The actual damage, however, would vary for different localities depending on the population density, types and number of structures, and property evaluation. If the accident were to occur in a wooded area proximate to a surburban or residential area, for example, a fire might occur which under favorable weather conditions might spread to an adjacent populated area and cause substantial loss.

Containment of the destructiveness of an accident is a third aspect of safety philosophy. Realizing that accidents may still occur even though efforts are made to protect the motor from an accident or to minimize their occurrence, protective measures may be taken to minimize the ensuing damage. Launchpad siting is a prime example of such measures considering various interpad distance, pad-to-control center distance, and exclusion zone requirements by range safety.

SUMMARY AND CONCLUSIONS

The systems approach to hazard analysis has been used to provide a logical, systematic, and flexible method for analyzing the potential hazards of the large solid motors. The graphic analysis, developed through modification of the fault tree technique and approximations of the systems parameters, portrays the real system and provides a qualitative estimate of the degree of safety of large motors during their proposed use. The development of the graphic model for each potential accident, illustrated in Figure 10 for "explosion in the surroundings," provides a means for suggesting considerations for improving safety or for recommending special tests or research efforts required to establish the system parameters.

The modifications to the fault tree still allow one to express the relationships mathematically using Boolean algebra. Also, assuming that necessary probability functions and dependent variable functions are available, simulation of the system can be accomplished using hybrid computation techniques. The primary problems remaining in the area of hazards analysis are the quantification of human factors, natural phenomena, and system parameters required for mathematical model simulation.

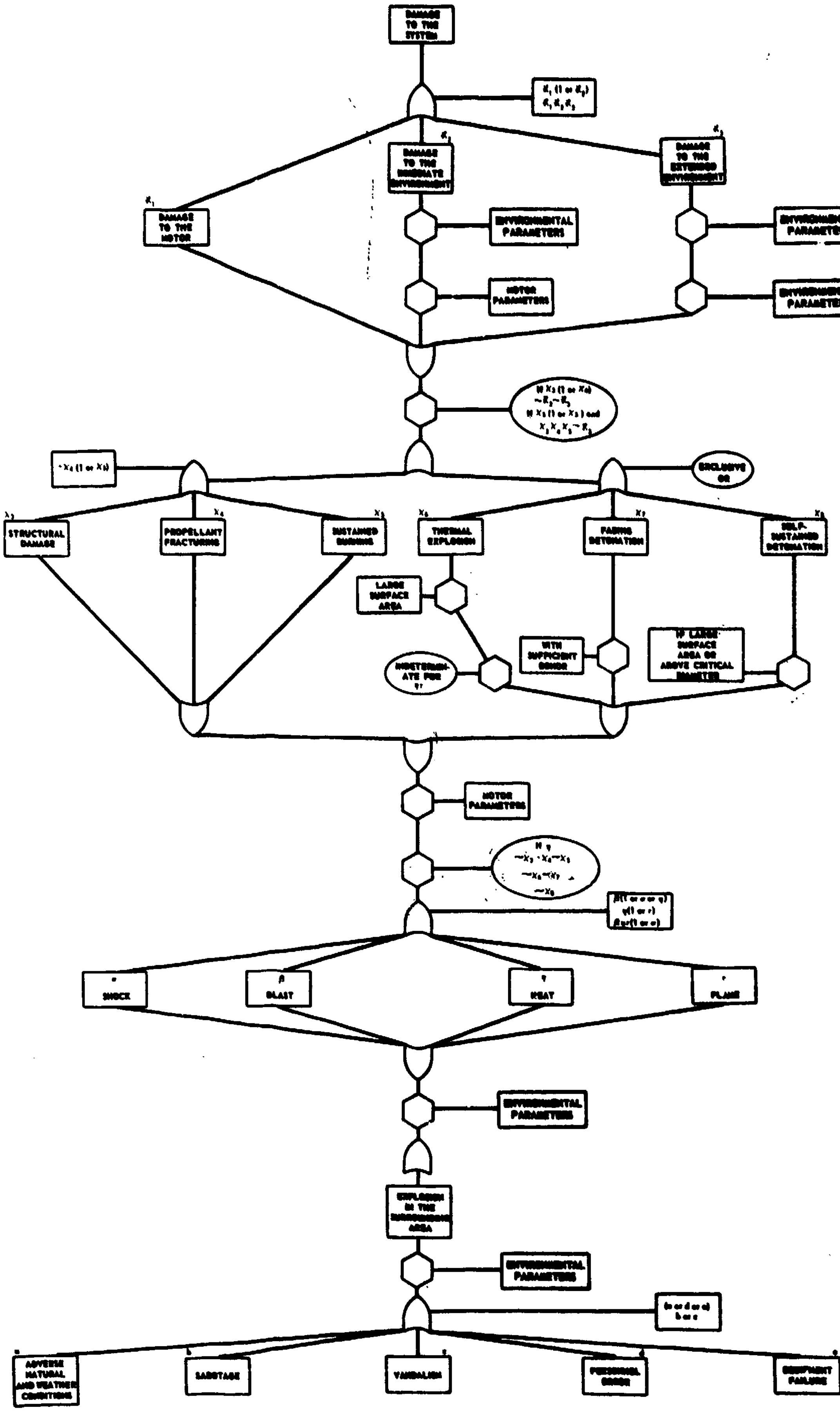

Figure 10. EXPLOSION IN THE SURROUNDINGS

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SOUTHEAST ASIA

Briefings regarding munitions safety matters in Southeast Asia were given by:

Mr. Jack W. Daniel, Pacific Air Forces

Capt. J. E. Taylor, USA, Missile Ammunition School, US Army Missile Command, Huntsville, Alabama

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HAZARD EVALUATION OF OTTO FUEL II

by

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This paper was not presented but is included for your information.

INTRODUCTION

Otto Fuel II, a liquid monopropellant, presents unique problems in safety engineering. It is the first monopropellant, other than hydrogen peroxide, to be placed into large scale use by the military. This fact alone has required the evaluation of potential hazards that are involved in the handling of a liquid monopropellant in fleet environment and the establishment of applicable standards and procedures for its handling and storage.

BACKGROUND

Otto Fuel II was developed specifically for use in torpedo engines in accordance with criteria vital to its intended application. These were defined as follows:

(1) The vapor pressure of the monopropellant must be as low as possible to preclude the formation of possible explosive mixtures and to prevent any significant physiological hazards.

(2) The diluent (desensitizer) must be water-insoluble. In the event of gross spillage and the requirement for a water rinse, there would be the danger of the diluent being carried away, leaving behind a sensitive explosive residue. The desensitizer in Otto Fuel II is soluble only to the extent of about 0.001%.

(3) The diluent must have a vapor pressure very nearly equal to that of the nitrate ester to prevent fractional distillation and recondensation which could result in stratification during long-term storage.

(4) The propellant and its components must have flash and flaming points sufficiently high so that at ambient temperatures and pressures the propellant in bulk cannot be ignited in air.

(5) Self-sustaining decomposition in a reactor, without the addition of an oxidizer, must take place at a minimum pressure of at least 100 psia. This is mandatory to prevent a widespread fire in case of reactor or line failure during operation. In other words, the decomposition process must be self-extinguishing upon the release of pressure.

(6) The thermal stability of the propellant must be excellent since it may be stored in areas of elevated temperatures during normal fleet operations.

After its formulation, Otto Fuel II was synthesized by the Naval Propellant Plant (NPP) in quantities sufficient to begin the extensive series of testing necessary to provide the characteristics of thermal decomposition; physical, chemical, and electrical properties; and safety limitations.

This paper presents the results of standard safety tests as well as the more specialized evaluations of the potential hazards in the intended application.

COMPOSITION AND PROPERTIES

Otto Fuel II was specifically formulated to possess certain properties which would make it an attractive monopropellant. Once formulated, an intensive effort was begun to determine all data applicable to its use, handling, and storage.

A summation of these data is included in the following tabulation.

Physical Properties

Density	1.2314 g/ml
Freezing point	-32° C (-25.6° F)
Vapor pressure of composition (dried)	0.0728 mm at 25° C
Vapor pressure of nitrate ester	0.09844 mm at 25° C
Viscosity	4.04 cp at 25° C
Surface tension	34.45 dynes/cm at 25° C
Fire point	127° C (260° F)
Specific heat	0.445 cal/g/°C at 25° C
Dielectric constant	18.8 at 23° C
Conductivity	14.2μ mhos/meter at 23° C

Solubilities

Water in Otto Fuel II	0.31% by weight at 25° C
Otto Fuel II in	
Acetone	Very soluble
Alcohols	Very soluble
Methylene chloride	Very soluble
Ethylene glycol	Insoluble
Propylene glycol	Insoluble
Kerosene	Slightly soluble
Heptane	Slightly soluble
Fuel oil	Slightly soluble

FIRE HAZARDS OF OTTO FUEL II

Otto Fuel II is a nonflammable liquid as defined by the Interstate Commerce Commission and by military service regulations. However, it can be ignited when it is dispersed as a fine spray. It can also be ignited when porous or absorbent materials are present such as paper, rags, and fiber glass.

Since Otto Fuel II is a monopropellant containing considerable energy, it was decided to obtain data on the hazards associated with it under various conditions of heating and ignition both in accidental and normal use. The fire hazard tests that were conducted in the absence of shock with Otto Fuel II may be divided into the following categories:

(1) Dripping fuel onto a heated surface

(2) Dripping fuel into a running electric motor

(3) Ignition of fuel-soaked rags with wooden match, electric squib, and bag igniter

(4) Burning the fuel in an open pan

(5) Heating of the fuel in gasoline cans and capped pipes

(6) Rapidly heating the fuel in U-shaped pipes.

An important feature of all the above tests was that no explosion took place. When closed vessels were involved, a pressure burst necessarily occurred.

A basic test which can be used to anticipate and interpret data obtained in various fire hazard tests is the differential thermal analysis test (DTA). It was found that the exotherm began at 265° F and reached a maximum at 320° F. At 380° F a maximum amount of smoking occurred. The material remaining after the exotherm appeared to be mostly charred.

Rapid heating to the vicinity of 400° F seems to have a different effect.

It was found that Otto Fuel II will ignite on striking a hot surface at about 400° F, even though no source of ignition such as a spark plug or a flame is nearby. Apparently, a sparking electric motor does not get hot enough to cause self-ignition of the monopropellant. A number of ignition tests were made with Otto Fuel II in open pans. In bulk, the fuel will not burn when attempts are made to ignite the liquid with an electric match. However, the liquid can be ignited, for example, in an open pan by means of rags soaked in Otto Fuel II or in fuel oil. The rags are ignited by a persistent flame such as a bag igniter or a wooden match. An ordinary squib or electric match is not of sufficient duration.

The similarities and differences between heating gasoline and Otto Fuel II when stored in vented or closed cans were investigated. In both cases burning of the fuel took place. In the case of gasoline, the vapors burned as they escaped from the pouring spout; in the case of Otto Fuel II, the can was ruptured both for the open spout situation and the closed container. A number of heating tests were made with Otto Fuel II in closed sections of straight pipe and in U-shaped pipes. The purpose was to determine if there would be any detonation from a rapid decomposition of the fuel in a vessel such as a surge tank. With the closed pipes a pressure burst occurred and it was found that three to seven large fragments were produced. The conclusion is that no detonation took place.

In the case of the U-shaped tubes, the venting area can be as small as one-sixteenth the cross-sectional area of the pipe (at each end of the pipe) and still adequately vent the fuel vapors.

EXPLOSION HAZARDS OF OTTO FUEL

Otto Fuel II has been found to be very insensitive to initiation by detonation effects at ambient temperature especially when unconfined or lightly confined. Otto Fuel II is not classified as an explosive. Hence, it is typical of a class of materials which must be considered potentially explosive until proven otherwise. A variety of detonation and shock tests were carried out as follows:

(1) Detonation of 75 pounds of Composition C-4 on top of a 5-gallon can of Otto Fuel II to determine the confinement effect caused by increasingly larger containers

(2) Critical diameter tests with a variety of confinement

(3) Card gap tests, modified Naval Ordnance Laboratory (NOL) type, to investigate shock sensitivity and the effect of temperature

(4) Flying plate impact test as a measure of the effect of adiabatic compression

(5) Bullet impact test to study the influence of projectiles from nearby explosions.

The large scale detonation tests were designed to determine under extreme conditions, i.e., at a weight ratio of 1.5:1.0 of booster explosive to acceptor charge, if the monopropellant would make a contribution to the detonation yield. The following crater sizes were obtained:

Test Description	Crater Size
75 lb of Composition C-4 stacked on top of a 5-gal. can of Otto Fuel II	6-foot diameter × 3-foot depth
Five, 5-gal. cans, each containing 75 lb of Composition C-4, surrounding a 5-gal. can of Otto Fuel II	15-foot diameter × 3-foot depth
75 lb of Composition C-4 stacked on top of a 5-gal. can of water	2-foot diameter × 1-foot depth

It is clear that a substantial contribution was obtained from Otto Fuel II in the two cases; however, the quantity of booster explosive was excessively large. Even with a large booster, some Otto Fuel II did not explosively react as evidenced by a large fireball and by the scattering of some propellant.

In the critical diameter tests it was found that when Otto Fuel II is contained in a schedule 40 pipe it will detonate when the internal diameter of the pipe is 1.375 inches. At smaller internal diameters, such as 1-inch, the heaviest confinement tested (0.378-inch wall) was not sufficient to permit propagation of a detonation in Otto Fuel II. Table I presents the available information.

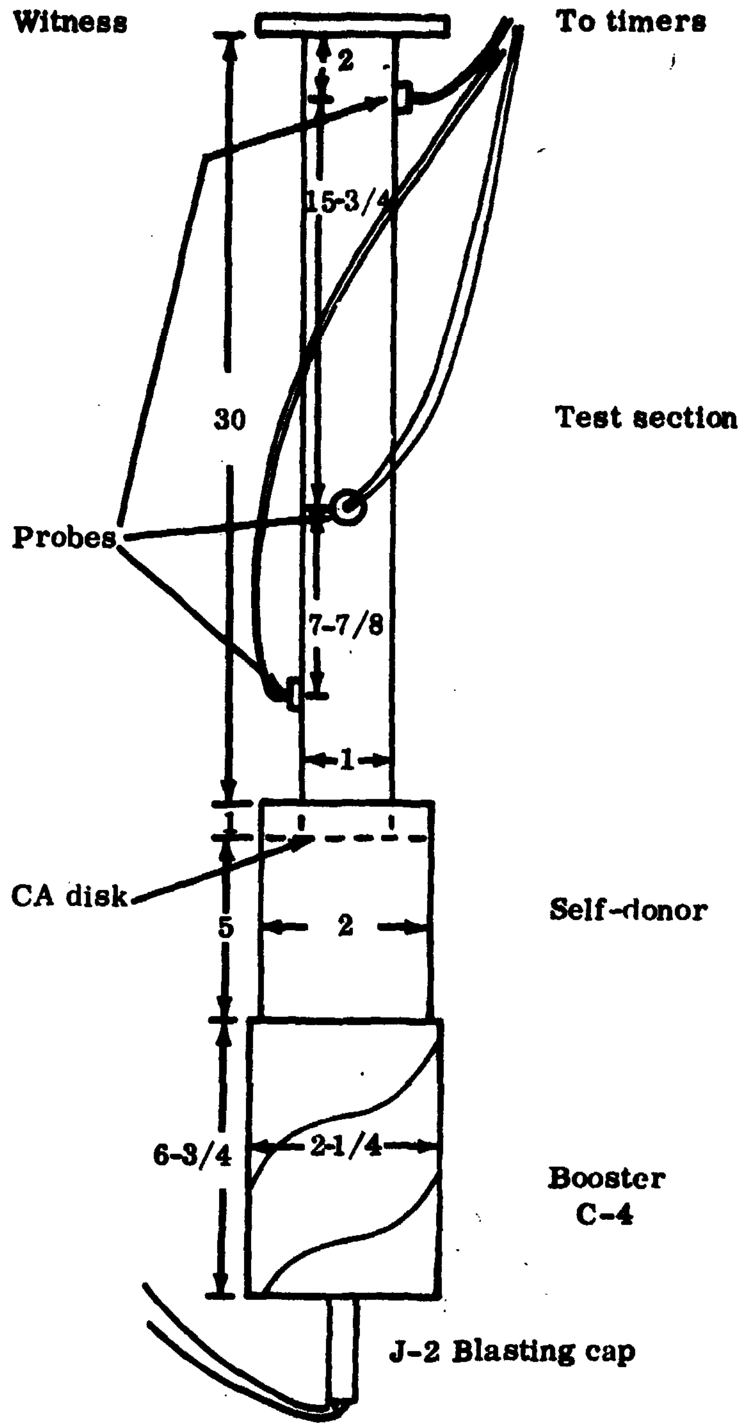
Table I

CRITICAL DIAMETER DATA ON OTTO FUEL II

Diameter (in.)	Wall thickness: Negative tests (in.)	Wall thickness: Positive tests (in.)	Wall thickness: For 50% point (in.)
1.000	0.378 (4-)		
1.375		0.140 (1+)	
1.500	0.07 (4-)	0.125 (1+, 3-)	0.250
4	0.035 (1-)		
6	0.100[1] (1-)	0.500 (1+)	
8	0.100[1] (1-)		
12		0.375 (1+)	

[1]Cardboard tubing.

In relatively little confinement (as cardboard tubes), Otto Fuel II will not detonate in 6- and 8-inch diameter containers (Table I). Considerable care was necessary in conducting critical diameter tests because the measured detonation velocity may fade when the length of the pipe or tube exceeds three or four diameters. Figure 1 shows the test equipment used as developed originally by the Bureau of Mines. Note especially the so-called "self-donor" section. The purpose of the latter is to insure that the detonation is not overdriven, which can easily lead to erroneous results.



(All dimensions are in inches)

FIGURE 1. TEST ASSEMBLY FOR OTTO FUEL II
(Developed by Bureau of Mines)

Probably the best known detonation test is the NOL card gap test. Since the critical diameter of Otto Fuel II in schedule 40 pipe is near 1-1/2 inches, the usual card gap containers of 1.44-inch diameter had to be replaced by a 2-inch diameter × 1/4-inch wall thickness pipe. Table II shows the card gap data obtained at three temperatures for Otto Fuel II and one value when carbon dioxide was bubbled through the liquid.

Table II

CARD GAP DATA FOR OTTO FUEL II[1,2]

Material	-45° F	80° F	78° C
Otto Fuel II	26.3 (0)	13.3 (0)	38.7 (0 to 13)
Otto Fuel II and carbon dioxide		46.3 (26)	

[1] 2-inch diameter × 0.25-inch wall thickness × 12-inch length steel tube.

[2] Numbers in parentheses are number of cards at 1.44 inches in diameter (NOL test).

For comparison the corresponding card gap values for the well known standard NOL card gap test are given in parentheses after the values given in Table II. It will be seen that at ambient temperature Otto Fuel II has a hypothetical zero card gap value by extrapolating to the conditions of the standard NOL conditions. A zero card gap value at ambient temperature indicates that the liquid fuel is either a Class B explosive or that it should not be identified as an explosive at all. A comparison between Otto Fuel II and hydrogen peroxide (90.7%) shows that hydrogen peroxide is more sensitive than Otto Fuel II. The data are as follows (at 50° C):

Otto Fuel II	5 cards or 0.05 inch
Hydrogen peroxide (90.7%)	11 cards or 0.11 inch

Some indication of the possible hazard caused by adiabatic compression is given by the card gap value with carbon dioxide bubbling through Otto Fuel II. The severity of the conditions involved and the moderate number of cards used (26 cards) lead to the preliminary conclusion that adiabatic compression is not a severe hazard.

Confirmation was obtained by conducting a number of "flying plate" tests (Figure 2).[1]

[1] Developed by Intermountain Research and Engineering Company for tests of Otto Fuel II.

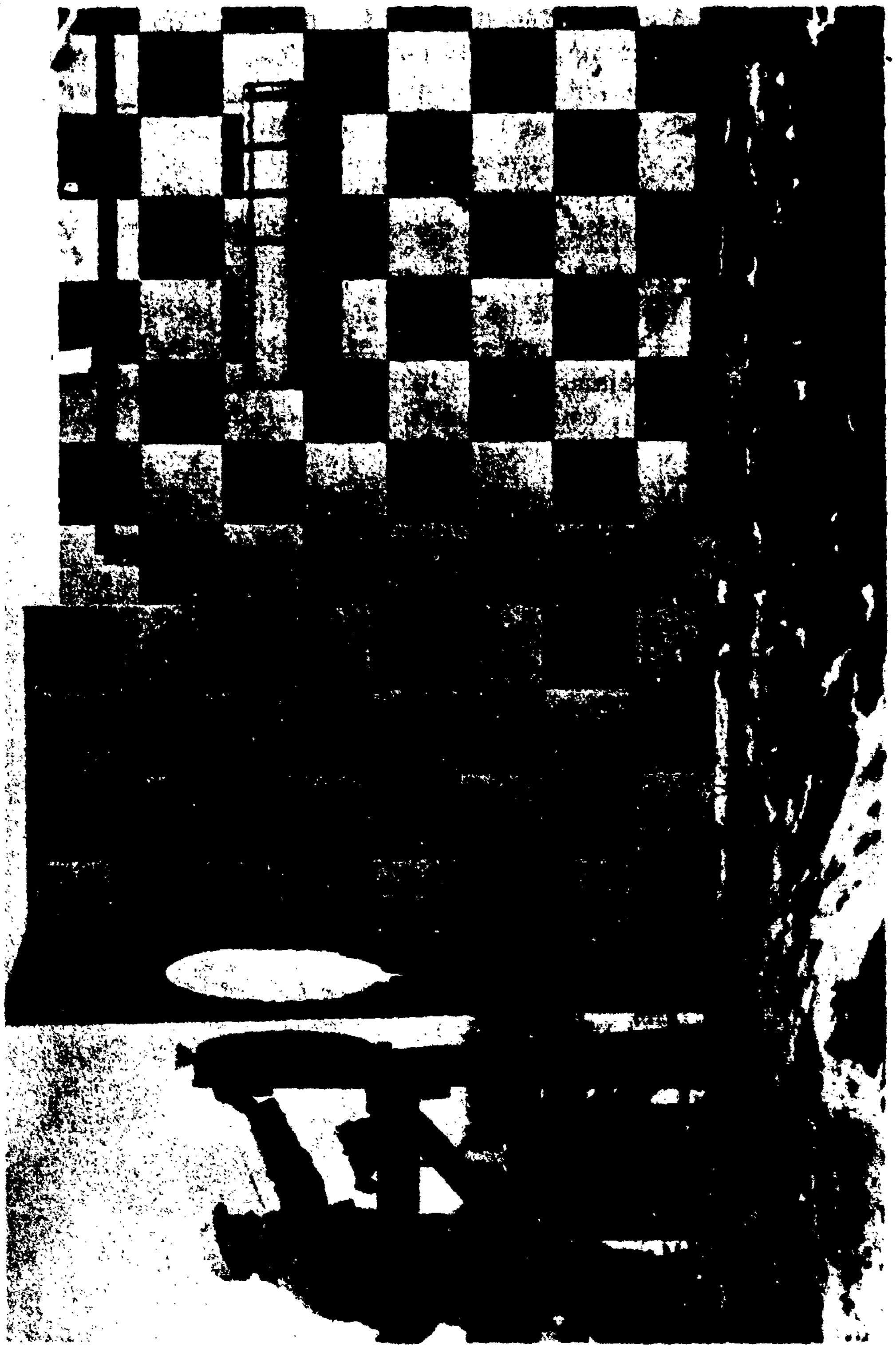


FIGURE 2. FLYING PLATE TEST APPARATUS
(Developed by Intermountain Research and Engineering Company)

In this test, a 250-pound plate travelling 185 to 200 feet/second was allowed to impact on a fuel tank partly filled with Otto Fuel II. The dimensions of the tank were: 12-inch diameter, 20-inch length, and 1/4-inch wall thickness. No explosive reaction was found in any of the trials. The tank ruptured immediately on impact of the plate, releasing a spray of monopropellant. Even though the vapors were ignited in two out of four trials, none of the liquid fuel caught on fire. The kinetic energy of the impacting plate was equivalent to a 55-gallon drum of the fuel traveling 125 feet/second.

A potential for a detonation is the impacting of fuel storage containers by high velocity fragments. Such conditions are reproduced by the bullet impact test. Eight tanks (13 inches in diameter × 14 inches in height) were exposed to 20 mm AP and 20 mm HEI bullets, causing tank rupture (as shown in Figure 3)

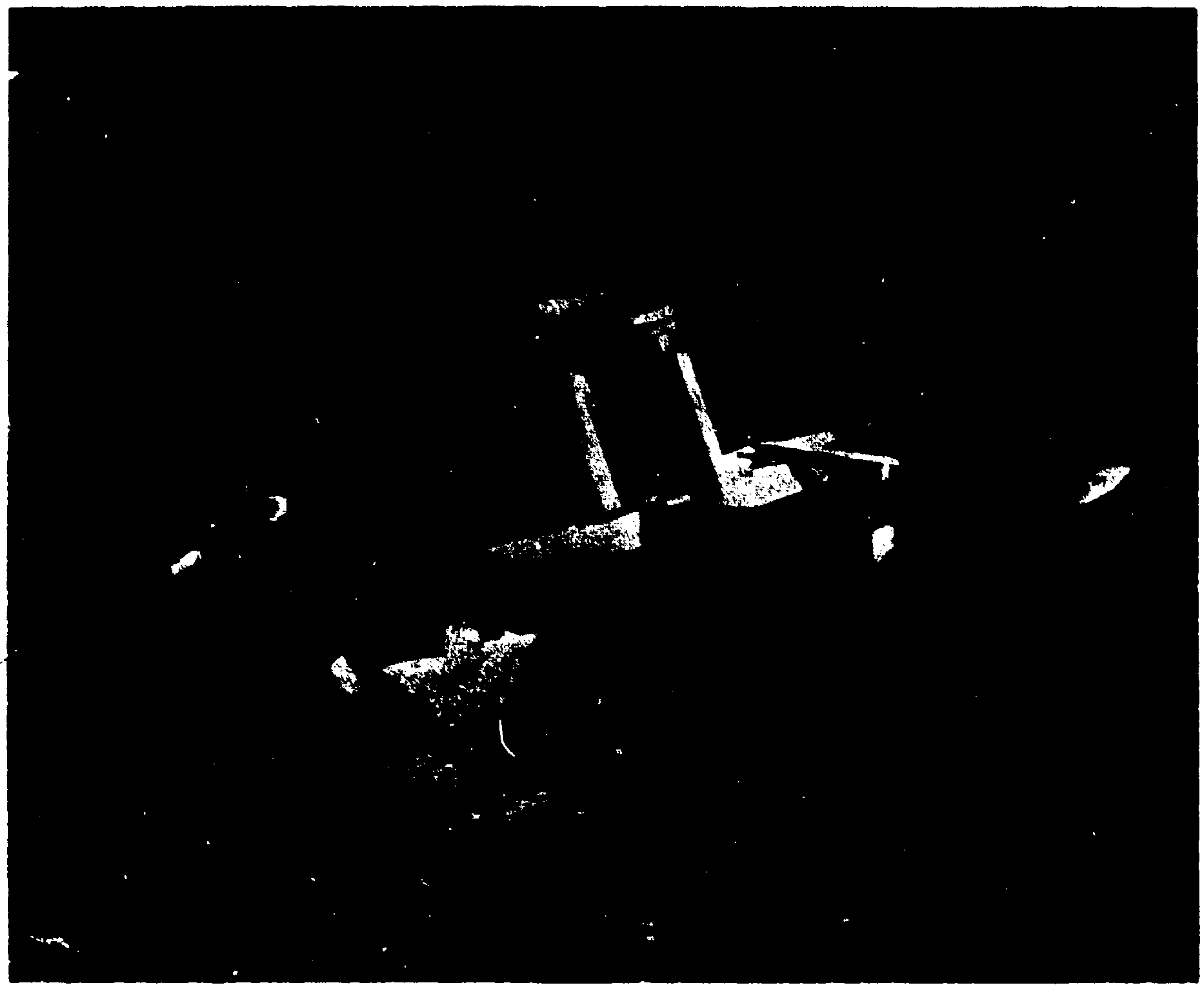


FIGURE 3. RESULT OF 20 MM HEI PROJECTILE ON MK 44 TANK

and unsustained burning. Fragments were thrown as far as 300 feet. Other tests with the fuel in capped, 2-inch-diameter nipples produced 1 pressure burst in 20 tests. No detonation resulted in any of the cases. The pressure bursts are similar to those obtained in heating closed containers.

In conclusion, Otto Fuel II is very difficult to detonate except under conditions of strong confinement or with an excessively large explosive booster.

COMPATIBILITY

The area of compatibility was originally approached by placing common materials of construction in contact with Otto Fuel II for about 1 week at mild temperatures. These contact tests were sufficient during the early developmental stages; but, when the material found applications in weapons systems, more extensive testing became necessary.

In this application, compatibility means the effect of the fuel on the test material and vice versa, as well as a determination of whether or not the observed interaction would be of significance in the intended application. Materials were evaluated as to whether they would be in constant contact, intermittent contact, or would contact the fuel only in abnormal circumstances. To simulate accelerated aging conditions, the materials to be tested were placed in contact with Otto Fuel II for periods ranging from a few minutes to several days and at temperatures up to 145° C.

Another study in the field of compatibility was initiated as a result of concern over the contamination of the fuel by common shipboard materials. These tests were carried out in much the same manner with the primary concern being the effect upon the fuel.

A partial listing of these test results is given in the following tabulation.

Material Contacted	Brief Description of Reactions
Chemicals:	
Water	Equal volumes remain in two phases. No titratable acid was released, indicating no hydrolysis after refluxing in excess of 2 hours.
Hydrazine hydrate (85%)	Equal volumes remain in two phases. On warming, the hydrazine layer distills.
Concentrated aqueous ammonia	Equal volumes remain in two phases. Warming evaporates the ammonia layer.

Hydrogen peroxide (90%)	Equal volumes remain in two phases. When warmed, the aqueous layer distills.
Sulfuric acid (95%)	Acid was added dropwise with stirring. The first few drops caused the solution to turn black. The temperature rose to 50° C and the addition of acid was stopped; heating continued spontaneously to over 110° C when there was a sudden charring of the entire reaction mixture and expulsion of carbonaceous puff balls. The copper wire holding the thermometer in place was covered with an oxide layer.
Nitric acid (70%)	Equal volumes react slowly without marked heat effect. When the mixture is heated, it fumes off, leaving a pasty mass.
Sodium hydroxide (solid)	No reaction at room temperature; but on warming, especially on addition of a little water, there is an extremely vigorous reaction with much evolution of heat. A waxy solid is the end product.
Red lead (Pb_3O_4)	No reaction, even when the mixture is heated briefly to the boiling point of Otto Fuel II.
Iron oxide (rust, Fe_2O_3)	No reaction even when heated.
Bleach (5.25% sodium hypochlorite solution)	An emulsion forms; reaction is slow. Analysis of the organic layer after reaction indicates that the nitrate ester is slowly attacked.
Metals:	
Stainless steels	No reaction.
90:10 Copper:nickel alloy	No affect on the metal. Contact with the copper, however, accelerates stabilizer depletion considerably and therefore, copper is not suitable for long-term contact situations.
Mild steel	No reaction.

Elastomers:	
Neoprene (rolled sheet)	Some interaction. Neoprene swells slightly (about 25%); small amounts of the neoprene or monomer dissolve.
Buna-N	There is considerable interaction. The Buna-N swells about 61% in volume at room temperature, about 74% at 145° F.
Butyl rubber	No interaction.
Silicone rubber	No interaction.
Teflon	No interaction.
Viton A	There is considerable interaction. The Viton swells to about three times its original volume after a week at 145° F and increases about 74% in volume after a week at room temperature.
Polyethylene	Little interaction. Polyethylene is stained bright yellow practically on contact. No swelling occurs.
Polyurethane (foam)	Little interaction. At 145° F some of Otto Fuel II is absorbed.
Natural rubber	Little interaction. The light-colored gum rubber is stained yellow. No swelling or dissolving of the rubber.
Lubricants:	
Kel-F lubricant	Partially soluble; forms a pasty mixture of two solid phases suspended in a liquid mixture.
Silicone lubricant	Almost no interaction even at 145° F (where the lubricant melts).
Covering Materials:	
Enamel	Forms a suspension of pigment in mixed solvents. Fuel removes finish from enameled surface.
Paint, water latex	Forms a two-phase mixture, partly emulsified. Otto Fuel II loosens the paint on a painted surface; finish can then be rubbed off.

Red lead primer	Forms a suspension of red lead in mixed solvents; no chemical reaction and no hazard. Otto Fuel II removes finish from primed surface.
Varnish	Miscible with Otto Fuel II which also removes the finish from a varnished surface.
Liquid and paste wax	Forms a suspension of undissolved wax in mixed solvent. Fuel penetrates wax on a waxed surface, but does not remove it.
Vinyl asbestos tile	The binder dissolves in 3 to 4 hours, even at room temperature, and the "tile" disintegrates.
Asphalt tile	The solvent and possibly some of the asphalt material dissolve within a few hours, even at room temperature. The "tiles" swell, increase about 50% in volume, and slowly disintegrate.
Miscellaneous:	
Concrete (crushed)	No interaction.
Cork	No interaction.
Glass	No interaction.

In each case where an interaction was noted between the fuel and the test material, a further test or analysis was carried out to determine the effect of the interaction. In the case of partial solution the residue of the extraction was subjected to impact sensitivity tests to check for selective extraction of one of the fuel's constituents which might leave a more sensitive residue. Some of these data are presented in the following tabulation.

Cavity Drop Tests on Extracted Otto Fuel II

Description of sample	Cavity drop test 50% figure (kg-cm)
Residue (30 ml) from extraction of 40 ml of Otto Fuel II by 100 ml of heptane	13.8
Residue (26 ml) from extraction of 40 ml of Otto Fuel II by 150 ml of heptane	7.0

Residue (31 ml) from extraction of 100 ml of Otto Fuel II by 310 ml of fuel oil no. 2	Above 80.0 (insensitive to limit of machine)
Residue (35 ml) from extraction of 45 ml of Otto Fuel II by 145 ml of motor oil no. 30 (stock no. 9150-231-6654, symbol 9250)	31.2
Residue (26 ml) from extraction of 45 ml of Otto Fuel II by 165 ml of kerosene	9.6
Residue (34 ml) from extraction of 55 ml of Otto Fuel II by 165 ml of paint thinner (light petroleum solvent)	12.5
100% Nitrate ester	3.4
Otto Fuel II	18.6

In general, oxidizing agents, strong acids, and strong bases are to be avoided as they may react vigorously with the fuel. Otto Fuel II is either inert to or enters into basically nonhazardous reactions with other than the above mentioned materials. Most saturated aliphatic hydrocarbons are miscible to some degree with Otto Fuel II. Many elastomers, as well as most paints and asphalt or vinyl floor tiles, are attacked to some degree by the fuel. In most of the reactions, it is the solution of Otto Fuel II in the test material, or vice versa, which renders the material unusable with Otto Fuel II, although no direct hazard results.

Until now, compatibility with materials has been the only subject discussed. There is one other relatively important area—toxicology. Extensive testing is being done using various animals as test subjects. Fatalities in animals have been caused by ingestion and by extended skin contact. Although dosage levels in animals cannot be meaningfully extrapolated to humans, it has been estimated that ingestion of 2 ounces of Otto Fuel II would kill a man-sized rabbit.

In the absence of specific data on the threshold limits for exposure to Otto Fuel II vapors, the best available means of providing more definitive guidelines to users appeared to be correlating this fuel with a chemically similar material. The material selected was ethylene glycol dinitrate which is felt to be somewhat more toxic than Otto Fuel II. Treating Otto Fuel II in a like manner should provide an extra margin of safety.

Although testing has continued for several years, little is yet known of the toxic effects of the fuel. Until such time as definite limitations can be set for exposure to the fuel, a primary aim in equipment design or procedural innovation will be to avoid contact with Otto Fuel II.

DESIGN OF INSTALLATIONS

Hardware and Facilities

This section is concerned primarily with the design of equipment for use in facilities engaged in the development and test of devices for use with Otto Fuel II. It is assumed that all of the normal precautions have been taken for operations involving explosives.

To offer guidelines to users and potential users of Otto Fuel II, a list of recommendations was formulated by a team of people experienced in the handling of the fuel. Virtually all of the recommendations are offered to avoid the potential hazards tested for and described previously in this paper. These recommendations, formulated in June 1965, are equally applicable today.

Hardware:

(1) Use detonation traps and check valves where applicable.

(2) Minimize propellant line diameters. Lines in excess of 1 inch in diameter are not to be used.

(3) Avoid stagnation pockets in high-pressure circuits.

(4) Minimize the volume of high-pressure circuits.

(5) Use adequate pressure relief devices, particularly in high-pressure circuits. Types of relief devices should be such that they prevent spraying or atomization of fuel.

(6) Provide adequate isolation between system components to minimize escalation of incidents.

(7) Minimize the possibility of gas being introduced into a fuel pump system by:

(a) Isolating Otto Fuel II from the pressurizing gas by a water layer or impervious bladder where feasible

(b) Eliminating pockets for possible gas accumulation in Otto Fuel II circuits

(c) Providing positive means to eliminate all gas pockets in the system prior to startup

(d) Paying particular attention to pump inlet conditions to minimize pressure drops and cavitation effects

(e) Minimizing pressure ratio used in a single stage of pumping.

(8) Avoid trapping Otto Fuel II between two closed valves.

(9) Design fail-safe and emergency shutdown systems which will rapidly remove pressure from the system and minimize Otto Fuel II spillage.

(10) The pump design should be such that the volume of fuel is minimized; the speed of the pump should be controlled so as to minimize rapid pressure rises in the fuel during startup.

(11) CAUTION: The bypassing of fuel from the pump discharge to the fuel storage tank or the pump suction should be avoided. The chief hazards are the increase in fuel temperature and the increase in absorbed gases.

Facilities:

(1) Provide positive personnel protection for the general public as well as test operators.

(2) Use indirect methods for viewing events in the test area.

(3) Use concrete flooring for storage and test area. (Concrete floors must be steel troweled at least twice to obtain a smooth, dense finish and coated with Mor-an-tuf epoxy paint or equal. Reference OP 3368.)

(4) Use dikes of sufficient height to contain 10% more than tank capacity in storage areas or provide adequate runoff to a disposal area.

(5) Minimize the amount of utility services in the test and storage areas, i.e., gas, steam, and electrical power.

(6) The use of explosion-proof electrical equipment is desirable where there is the possibility of Otto Fuel II vapors or spray.

(7) Use only those facilities which contain adequate casualty control measures, i.e., fire control, containment, isolation, or adequate draining.

(8) Test and storage areas shall be of fire resistant construction.

(9) Test and storage areas shall be clean and the area free of combustibles.

OPERATIONS

Otto Fuel II is relatively safe to handle; however, there are some basic guidelines to be followed in operations as well as in design of equipment and facilities involving the use of Otto Fuel II. The following excerpts from OP 3368 (Safety and Handling Instructions - Otto Fuel II) are recommended as basic, good safety practices:

<u>General</u>:

1. Operations should be controlled by standardized procedures and checklists.

2. Only trained personnel shall conduct these operations.

3. Good housekeeping practices shall be observed.

4. Spills are to be avoided since arduous cleanup and decontamination procedures are required.

5. The fuel must not be flushed into common drainage systems.

6. Complete decontamination must precede welding of material contaminated by Otto Fuel II.

<u>Personnel Safety</u>:

1. Personnel shall be well briefed on the nature and properties of the fuel.

2. Primary toxic symptom of exposure to the fuel is a severe headache. Exposure to the liquid or its vapors is to be avoided or minimized.

3. Safety equipment appropriate to the operation shall be available and its use shall be mandatory.

4. Where gross spillage is probable, forced air ventilation systems shall be employed.

CONCLUSIONS

Otto Fuel II has not been detonated when exposed to heat, either confined or unconfined. The liquid fuel is hard to detonate except under conditions of strong confinement or with an excessively large booster. Compatability tests show that strong acids and bases can cause vigorous reactions. On the other hand, the vast majority of chemicals and materials of construction are inert.

In the transferring, pumping, and storing of Otto Fuel II, precautions are recommended, particularly at high pressures, to avoid the introduction of gas into the system. For severe service requirements the use of ventilation and explosion-proof electrical motors are recommended.

In summary the hazard evaluation of a nonexplosive monopropellant has been described for conditions ranging to extreme severity of temperature and pressure.

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MEMORANDUM FOR DDESB RECORDS

SUBJECT: Declassification of Explosives Safety Seminar Minutes

References: (a) Department of Defense 5200.1-R Information Security Program, 14 Jan 1997

(b) Executive Order 12958, 14 October 1995 Classified National Security Information

In accordance with reference (a) and (b) downgrading of information to a lower level of classification is appropriate when the information no longer requires protection at the originally level, therefore the following DoD Explosives Safety Seminar minutes are declassified:

a. AD#335188 Minutes from Seminar held 10-11 June 1959.
b. AD#332709 Minutes from Seminar held 12-14 July 1960.
c. AD#332711 Minutes from Seminar held 8-10 August 1961.
d. AD#332710 Minutes from Seminar held 7-9 August 1962.
e. AD#346196 Minutes from Seminar held 20-22 August 1963.
f. AD#456999 Minutes from Seminar held 18-20 August 1964.
g. AD#368108 Minutes from Seminar held 24-26 August 1965.
h. AD#801103 Minutes from Seminar held 9-11 August 1966.
i. AD#824044 Minutes from Seminar held 15-17 August 1967.
j. AD#846612 and AD#394775 Minutes from Seminar held 13-15 August 1968.
k. AD#862868 and AD#861893 Minutes from Seminar held 9-10 September 1969.

The DoD Explosives Safety Seminar minutes listed above are considered to be public release, distribution unlimited.

Daniel T. Tompkins

DANIEL T. TOMPKINS
Colonel, USAF
Chairman

Attachments:
1. Cover pages of minutes

cc:
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MINUTES
OF THE EIGHTH
EXPLOSIVES SAFETY SEMINAR
ON
HIGH-ENERGY PROPELLANTS

GEO. C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

9-11 August 1966

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